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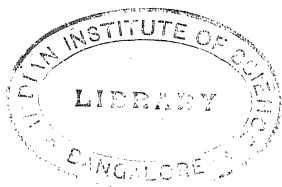
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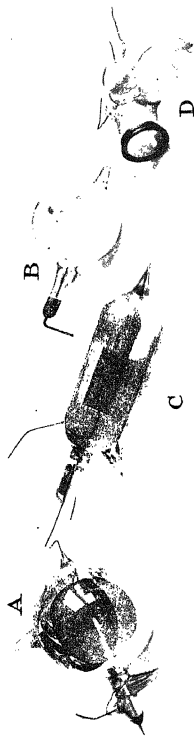
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TYPES OF PHOTOELECTRIC CELLS

Prontispiece

PHOTOELECTRIC CELLS

THEIR PROPERTIES, USE, AND
APPLICATIONS

BY
NORMAN ROBERT CAMPBELL
AND
DOROTHY RITCHIE

MEMBERS OF THE RESEARCH STAFF OF THE
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PREFACE

THERE are two devices which can detect or measure light by electrical means, the selenium cell and the photoelectric cell. Their history is curiously different. From its first discovery, the change in the conductivity of selenium when illuminated attracted the attention of the inventor rather than of the theorist, to whom it long remained an isolated fact of no special significance. The photoelectric effect, on the other hand, is one of the corner stones of physical theory; but until recently its practical potentialities were entirely unrecognized outside the laboratory, and insufficiently recognized within it. While the immense literature of selenium is directed mainly to its use, in the yet larger literature of the photoelectric effect its use receives scant attention.

The aim of this book is to redress the balance. Here we propose to regard the photoelectric cell, not as an illustration of important laws and theories, but as a laboratory or workshop tool. That does not mean that our outlook will be purely empirical, and that we shall offer nothing but a collection of unrelated facts and recipes; for we hold that experiment is a science as well as an art; but it does mean that we shall consider principles and theories only in so far as they bear upon practice.

Two difficulties immediately arise, one from the limitations of our own knowledge, the other from that of our readers. Practical treatises are seldom of much service unless they are based on personal experience; we cannot pretend to have immediate knowledge of all the devices we have to describe. We have thought it wise, therefore, to devote more space to problems and methods that we ourselves have studied and used than to those we have not, hoping thereby that what our exposition loses in width it will gain in depth. On the other hand, we have tried at least to mention all the larger problems and all the sound methods of which we have been able to learn by search of published literature and personal inquiry; and we have indicated where further

information concerning them can be found. And here we would explain that our notes do not constitute a bibliography; they make no pretence to give complete "references," or to trace all ideas to their fountain-head in the manner which (according to modern fashion) would be appropriate in a scientific treatise. They are intended to supplement the text, not to support it; the fuller the discussion in the text, the less the need for notes.

Again, our readers possibly vary from professional physicists to amateurs who know all about wireless. This difficulty we have tried to surmount by adapting the treatment of each topic to the class whom it is likely to interest. In some places we have assumed much knowledge, in others little; we can hardly hope that our guess at our readers' need is always right, but no other course seems possible.

Lastly, we have to explain that we are editors rather than authors of the book; for it could never have been written if we had not been able to draw freely on the great and varied knowledge of our colleagues. We would more particularly express our thanks to the Director, Mr. C. C. Paterson, for his leave to write on matters connected with our official work; to Miss M. K. Freeth who made most of the measurements upon which Chapter IV is largely based; to Mr. G. H. Wilson and Mr. T. M. C. Lance for reading the book in manuscript and proof.

N. R. C.
D. R.

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PHOTOELECTRIC CELLS

PART I

THEORY OF PHOTOELECTRIC CELLS

CHAPTER I

A GENERAL SURVEY

The Fundamental Processes.

WHEN light falls upon certain metals it causes them to emit electrons, just as the filament of a thermionic valve emits electrons when it is hot. The rate at which electrons are emitted is proportional to the amount of light. If the illuminated metal is the cathode of an electric circuit and some neighbouring conductor the anode, a current will flow in the circuit varying with the intensity of the light, just as a current flows in the anode-filament circuit of a thermionic valve.

This emission of electrons under the influence of light has been known, almost from its first discovery, as the photoelectric effect. There are other electrical changes produced by light to which this term might have been applied with equal propriety; and the denial of the term *photoelectric* to devices (such as selenium cells) that use these other changes cannot be justified etymologically or, perhaps, even scientifically (cf. page 20); indeed, recently there has been a tendency to give the term a wider meaning. But this tendency is unfortunate. Other names are available for devices which use other effects—thus selenium cells might be termed photo-conductive—while no other has been invented for those that we are about to consider. In this book, at least, a photoelectric cell will always mean one in which light produces an emission of electrons.

The photoelectric current carried by the emitted electrons is very small, much smaller than that flowing in a

thermionic valve. In a typical cell, with a window 3 cm. in diameter, exposed to a 100 watt lamp at a distance of 20 cm., this current is about 1 microampere. Accordingly, methods of amplifying photoelectric currents have always received much attention. Methods in which the current is amplified outside the cell, or at any rate by the introduction of electric circuits not essential to the cell, will concern us later. But there is a method, by which the current can be amplified within the cell, that is so closely associated with the photoelectric effect that it must be noticed immediately. When electrons travel with sufficient speed through a gas, they break the molecules that they encounter and detach electrons from them; these electrons pass on with the primary electrons and add to their number. This process is known as ionization by collision. By filling with gas the space between the cathode and the anode of a photoelectric cell and applying comparatively large electric fields, the number of electrons arriving at the anode can be made very much greater than the number leaving the cathode; the primary current due to the emission of electrons from the cathode is greatly magnified. Cells in which the current is thus magnified are called gas-filled cells, in distinction from vacuum cells in which there is no magnification.

The merit of cells is often judged by the magnitude of the current that they give when a prescribed amount of light is incident on them. We shall see later that there are often other considerations to be taken into account, which may upset a judgment made on this ground alone. But the three factors that determine this current are always important: they are—

1. The proportion of the incident light which falls on the cathode.
2. The ratio of the primary photoelectric current to the incident light.
3. The magnification by gas-filling.

The discussion of the last two factors will occupy most of the first part of this book; but before entering into details, it will be convenient to take a general survey of the whole field. Perhaps the best way to do this is to examine various types of cell that are being used at present, and to ask how their design has been influenced by these and by other minor factors.

The frontispiece shows the general appearance of four photoelectric cells that have been selected to illustrate the

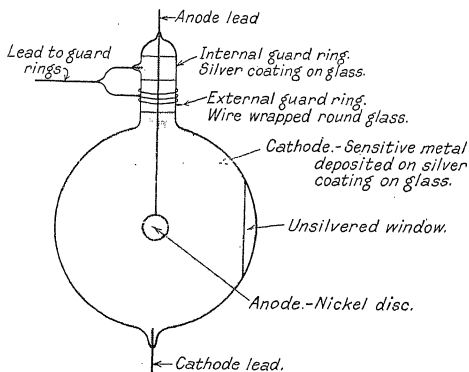


FIG. 1A. TYPE A

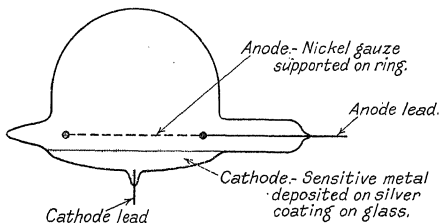


FIG. 1B. TYPE B

TYPES OF PHOTOELECTRIC CELLS

main principles involved. Fig. 1 (continued on pp. 5, 6, 7) shows their internal construction, together with that of some other cells not shown in the frontispiece.

The Photoelectric Metals.

The second of our three factors is determined by the material of the cathode. When the cell is to be used with visible light (as distinguished from ultra-violet light), our choice in this matter is closely limited; for there are only seven metals known that are sensitive at all to such light. They are sodium, potassium, rubidium, caesium, lithium, strontium, barium. All these metals are highly reactive chemically, and oxidize rapidly in the air. They must not only be enclosed in a sealed vessel, but they must be prepared in it; we cannot make our cathode in the open air and then introduce it into the cell. The most convenient method of preparing a clean surface of any material in a sealed vessel is to introduce the material as vapour and to condense it in the desired position. The first four of the metals named can be distilled in glass vessels; the last three cannot. This is the reason why so few attempts have been made to use them; very few facts about their photoelectric properties are available, and such as there are do not indicate that they would be preferable to the first four; but the real reason why they have not been used is the difficulty of preparation.

The possibility of distillation has influenced the design of the cell as well as the choice of metal. The metal is most easily condensed on the wall of the vessel, and the cathode is usually a layer of the metal on the wall (as in types *A* and *B*). In order that the drops of condensed metal may make good contact with each other and the lead to the exterior, the layer is usually deposited on a film of silver deposited chemically on the glass. But it is not necessary that the cathode should be part of the exterior wall; by careful treatment the metal can be condensed on a plate supported away from the walls, while it is driven from the walls by careful heating (as in types *C* and *D*). This point needs rather closer consideration.

Although the bulk of the metal can be driven from the wall of the vessel, and a window thus left for the entry of light, a thin film of it always remains. This film is photoelectrically sensitive, but, as it is very thin and deposited on an insulating surface, it has a very high resistance, and

is not in good electrical connection with the lead to the exterior. In types *A*, *B*, *E*, *F*, where the wall of the vessel is the cathode, the film covering the window is fully exposed

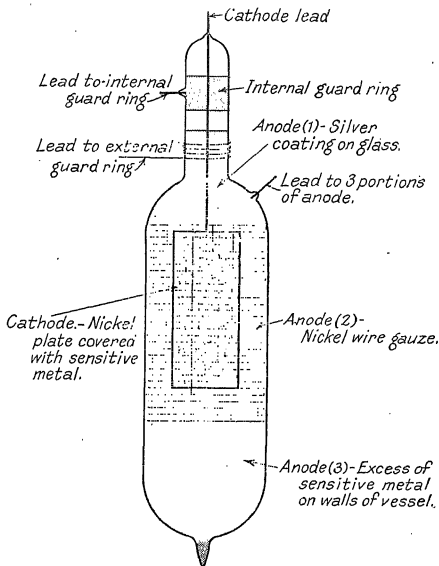


FIG. 1c. TYPE C

TYPE OF PHOTOELECTRIC CELL

to the light, and is in partial, but not perfect, connection with the cathode; it therefore makes an irregular contribution to the whole photoelectric current. But in types *C* and *D*, the part of the film that is exposed to the light is connected to the anode rather than to the cathode, and makes

no contribution to the current. The only part of the glass wall connected partially to the cathode is the small area forming the insulation of the cathode support, and this part can be shielded from the light. Types *C* and *D* are, therefore, slightly more regular in their action than types *A* and *B*.

But the presence of the thin film of the metal on parts

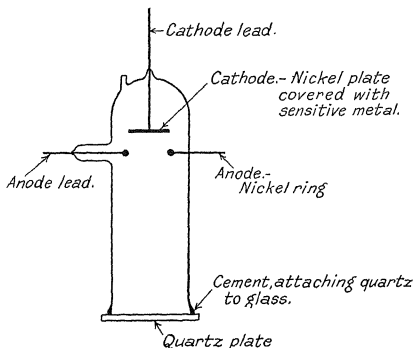


FIG. 1D. TYPE D

TYPE OF PHOTOELECTRIC CELL

of the cell other than the intended cathode has two other effects of, perhaps, more importance. The first is that the cell will always give some photoelectric current even when its connections are reversed; there will always be some of the active metal on the electrode that is intended to be the anode, and, if this electrode is made the cathode, a photoelectric current will flow when it is illuminated. If the anode has a much smaller area than the cathode, as in all types except *C*, the reversed current will be small; but it is important in some applications (cf. page 146). The second effect is due to the conductivity of the film; there may be electrical leakage across the surfaces of glass that are intended

to insulate the electrodes from each other. This trouble is more serious in some types of cell than in others; it is provided for, partially, by the insertion of guard rings, consisting of rings of silver deposited on the glass and connected to earth. Leakage from one electrode to the other is thus prevented, but not leakage to earth.

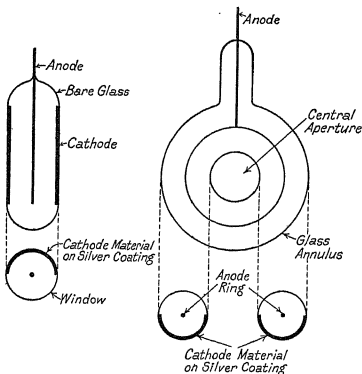


FIG. 1E. TYPE E.

FIG. 1F. TYPE F

TYPES OF PHOTOELECTRIC CELLS

Optical Problems.

We turn now to the first factor. If the cell is to be used with diffused light, such as daylight, the amount of light that will fall on the cathode is simply proportional to its area, or to the area of the window, if this is smaller than the cathode. The only way to increase the amount of light is to make a very large cell. Cells with cathodes up to 500 sq. cm. in area have been used for daylight recording, and in television when the object is scanned by a moving point of light. But more often the light can be concentrated on the cell by lenses; then the area of the cathode

and of the window are immaterial so long as they are large enough to admit the whole of the beam. This is a very important point; for there is a difference here between photoelectric and selenium cells. In the selenium cell the effect depends on the average intensity of the illumination, but in the photoelectric cell it depends only on the whole amount of light. So long as the light reaches the cathode, it makes practically no difference how the light is distributed over the cathode. Optical imperfections in the glass wall make no difference so long as they do not deflect any part of the light from the cathode; if they merely spread it out over the cathode they will do good rather than harm.

On the other hand, of course, there must not be any opaque objects between the window and the cathode; and in particular the anode must not intervene, or, if it does intervene, must be made of fine gauze which absorbs a very small fraction of the light. On this ground a ring is generally preferred to the plate in type *A*; but a plate with its edge turned to the light is unobjectionable. Again, if ultra-violet light to which the glass is opaque is to be used, a window of quartz must be provided through which the light can enter (type *D*).

All this is obvious. The only two constructions interesting from this point of view are types *A* and *F*. The cathode reflects some of the light incident upon it. In all the cells except type *A*, this reflected light leaves the cell and produces no further effect; but in this type, if the area of the window is small compared with the whole area of the wall forming the cathode, most of it falls again on another part of the cathode and may produce a further photoelectric effect. The principle involved is the same as that used in making the "black-bodies" employed in the study of thermal radiation, and cells of this type are sometimes called black-body cells. However, for reasons that will appear presently, cells of this type have no balance of advantage and are disappearing from use, except for special purposes. Type *F* was designed for picture-teleggraphy; an intense spot of light is concentrated on the picture through the central opening, and the light diffusely reflected from it received by the annulus. Here, again, the idea is ingenious, but is attended by drawbacks which more than counterbalance its advantages.

The Electric Field.

In a vacuum cell the shape and size of the electrodes make no difference to the current produced by a given photoelectric emission; for if a strong enough electric field is applied, all the electrons emitted can be dragged to the anode. But in the gas-filled cell, where magnification has to be produced by ionization by collision, the shape and size are of considerable importance. We shall discuss their influence later; but we may anticipate the conclusions at which we shall arrive by saying that cells in which the electric field is comparatively uniform have certain advantages over those in which it is much stronger in the neighbourhood of the anode than in the neighbourhood of the cathode. Unless the anode is very large compared with the cathode—an arrangement which presents difficulty on optical grounds—the two electrodes should be nearly of the same size and approximate to parallel planes. From this point of view type *B* has an advantage over type *A*, while type *E*, which has great merits on constructional grounds, is intermediate. Again, very small cells are disadvantageous, although they are more convenient for many purposes; for example, when they have to be fitted into a small space in a cinema projector for reproducing "talking films." The effect of the size and shape of the cell upon the magnification obtainable has not been studied very completely, and such conclusions as have been established have not always been applied. The tendency has usually been to design the cell to suit the apparatus with which it is to be used, and if the utmost sensitivity is not essential, this is doubtless the proper course; but if it is essential, the cell must be designed first and the apparatus adapted to fit it.

This general survey is intended primarily to introduce the novice to facts and ideas, without which he could hardly follow the more detailed discussions to which we must now proceed; but it may possibly serve another purpose, if it reminds the instructed reader how entangled are the problems of the photoelectric cell, and how impossible it is to solve one of them without consideration of the others. We shall now discuss in turn the two chief problems, the photoelectric emission and the voltage characteristic; minor problems that have not been mentioned already will appear

incidentally. In Chapter VII we shall discuss the bearing of our conclusions upon the choice of a photoelectric cell suitable for various problems.

HISTORICAL NOTE

Though we are not here concerned with history, we may perhaps mention that the photoelectric effect was discovered by Hallwachs in 1888. The pioneers in its application to the measurement of visible light were Elster and Geitel; by 1905 they had established all the main principles, apart from amplification by thermionic valves, but little use was made of their work till much later.

CHAPTER II

THE PHOTOELECTRIC EFFECT

THE first of our problems may seem very simple. If the primary current due to a given light is determined by the metal forming the cathode, and if there are only four (or possibly seven) metals that give any current at all, it is surely easy to decide which of them is the best. But the matter is much more complicated than it appears at first sight; so complicated indeed, that, although the theoretical importance of the photoelectric effect has led to a very thorough investigation of the facts, those facts which are of particular importance in the practical applications of the effect are still not known completely, and, even when they are known, are not completely explained. For this reason we should, perhaps, be justified in ignoring the theory completely in a book concerned with the use of photoelectric cells. But though theory cannot as yet resolve the complications, it does show why they exist; without it an understanding of the necessary limitations of photoelectric cells is impossible. It will be worth while, therefore, to inquire briefly how and why the incidence of light upon a metal causes the emission of electrons from it.*

Electrons in Metals.

The electrons that form part of every material body are retained within it by the attraction of the negative charges that they bear for the positive charges residing on the atoms. In non-metallic bodies (electrical insulators), each electron is more or less fixed in position and bound to certain atoms;

* There are two good English textbooks on photoelectricity: H. S. Allen, *Photoelectricity, the Liberation of Electrons by Light* (Longmans, 1925); A. L. Hughes, *Photoelectricity* (Cambridge University Press, 1914). The latest comprehensive work is by B. Gudden, *Lichtelektrische Erscheinungen* (Julius Springer, Berlin, 1928). It contains a bibliography up to 1927, which is complete on the theoretical side but does not pretend to cover the practical side completely.

To these works the reader is referred for all the facts of theoretical rather than practical interest which are omitted in this and the succeeding chapters.

in metallic bodies (electrical conductors), some of the electrons are free; they are not attached to particular atoms, but wander throughout the interior of the metal. Their wanderings are closely restrained only when they approach the boundary of the metal. Here the attraction of the atoms within the boundary is not balanced by an attraction of atoms outside it, and the electrons cannot pass through the boundary, unless they approach it with a speed and a kinetic energy sufficient to carry them out against the unbalanced attraction. But if an electron approaches with a sufficient energy, then it can break through the boundary and wander free again in the space beyond. Electrons in a metal are thus somewhat similar to marbles in a soup-plate. So long as the marbles roll about the bottom of the plate they are free; and they are free again if they escape from the plate and roll about the table. But they cannot escape from the plate unless they acquire sufficient speed and energy to climb the rim against their own weight and fall down on the outer side.

The energy that an electron must possess in order that it may break through the boundary of a metal into an empty space beyond, or, in our analogy, the height of the rim of the soup-plate, is a definite characteristic of the metal, the same for all specimens of the same chemically pure metal, but different for different metals. It is called the "work function"; it is usually denoted by ϕ and expressed in volts. For any charged body, bearing a charge e , in moving between two points between which there is a difference of potential of V volts, acquires a kinetic energy eV . The charge e on every electron is the same; consequently, every electron acquires the same energy in falling through the same voltage, and in order to specify the energy that an electron possesses, it is sufficient to specify the voltage through which it would have had to fall in order to acquire that energy. In the following list the column headed by ϕ gives the work-functions in volts of a few metals; the meaning of the third column will be explained presently (page 16). It will be seen that the range of possible values of the work function is comparatively small; no metal has a value larger than that of platinum, and none a value smaller than that of caesium.

TABLE I

Metal	ϕ (work function)	λ (threshold)
Pt . . .	6.30 volts	196 $m\mu$
W . . .	4.54 "	272 "
Cd . . .	3.94 "	313 "
Na . . .	2.05 "	600 "
K . . .	1.90 "	650 "
Rb . . .	1.69 "	730 "
Cs . . .	1.54 "	800 "

(It will be explained in Chapter III that a certain ambiguity attaches to all these values.)

The Emission of Electrons.

There are two ways in which the electrons may acquire energy greater than the work function, and thus become able to emerge through the surface of the metal. First, they may acquire it from the heat energy of the atoms. The laws governing the relation between the energies of the electrons and the temperature of the metal in which they are contained are very complicated—much more complicated than was imagined a few years ago. We need not discuss them in detail: it is sufficient for us to note that at any temperature the energies of the individual electrons vary over a very wide range, and that the proportion of them having at any moment energy above any assigned limit (and, in particular, above the work function) increases rapidly with the temperature. Even at room temperatures an electron must occasionally acquire enough heat energy to enable it to emerge, even from a metal with a large work function, such as tungsten; but the number that acquire such energy in any reasonable time is so small that it is impossible to detect their emergence experimentally. At high temperatures, on the other hand, the rate at which electrons acquire such energy is very much greater; although the mean energy of all the electrons in the metal may be very much less than the work function, the proportion of them that have a greater energy at any moment is sufficient to produce an appreciable flow of electrons from the metal. This flow, increasing rapidly as the temperature is raised and, at a given temperature, much greater from a metal of low work

function than from one of high work function, is the thermionic emission upon which the action of all thermionic valves depends.

Second, the electrons may receive energy from the radiation of which visible light is one special form. It is hardly necessary to explain nowadays that there is an essential similarity between all the forms of radiation known as wireless (long and short wave), heat (or infra-red) radiation, visible light, ultra-violet light, X-rays, γ -rays, cosmic rays: they are all waves, and waves of the same kind, differing only in their wavelength, which decreases along the series from many kilometres at one end to billionths of a centimetre at the other. Visible light is merely the form of radiation to which our eyes happen to be sensitive, and all eyes are not sensitive over exactly the same range; the distinction between light and other radiation is physiological, not physical, and in what follows the word *light* must be interpreted to include all of them, unless the qualification *visible* is added.

When electrons receive energy from a source emitting a discontinuous spectrum, consisting of light of a single wavelength, or a finite number of separate wavelengths, the law governing the amount of energy that they acquire is extremely simple. Light of a single wavelength, emitted by such a source, is always derived from electrons in the source which lose energy in emitting the light; and the character of the light is determined by the energy lost in emitting it. The law is that each electron in the metal that acquires energy from the source receives precisely the amount of energy which was lost by the electron in the source when the light was emitted. If the source emits a continuous spectrum, it is impossible to associate any particular part of that spectrum with the loss of energy of a particular electron; but the character of the spectrum is still determined by the losses of the electrons of the source as a whole, and these losses are reproduced statistically in the gains of the electrons of the recipient; if electrons in the source lose an energy W_1 twice as often as an energy W_2 , then the electrons in the recipient will gain W_1 twice as often as W_2 .

The law is so simple that if, in dealing with optical problems, we were interested in nothing but changes of energy,

we should never use the conception of light at all. There would be no object in introducing an agency to take energy from the emitting electron and give it to the receiving electron; we should simply say that the energy is transferred unaltered from the electron in the source to the electron in the recipient, and should never think of inquiring why it is so transferred. Further, we should know nothing about wavelengths; the character of light would be determined wholly by the loss of energy associated with its emission and the gain associated with its absorption. But when we come to consider, not merely how much energy is transferred, but also the spatial and temporal relations that must subsist between the source and the recipient, if one is to receive energy from the other, then we are forced to introduce the idea of an agency travelling along a definite path with a definite velocity and possessing a definite wavelength.

The laws determining the path by which energy travels are quite distinct from those determining how much energy is transferred; indeed, it has been the greatest problem of physics for the past twenty years to reconcile them. Even now, when the problem is nearly solved, there is still something anomalous in formulating one set of laws in terms derived from the other; and any explanation of why both sets are true is out of the question. Light is simply a name for the agency that transfers energy from one set of electrons to another in a certain way; the photoelectric effect is the primary and fundamental effect of light, and all others are secondary; it is meaningless to inquire why light exerts that effect, and why energy is always transferred by light in bundles or *quantums* of finite size. We should not ask how photoelectric cells can detect the light which the eye can see; we should ask rather how the photoelectric effect, displayed in its simplest form by the cell, can determine a process as complicated as vision.

The Threshold.

Fortunately, the law of the transference of energy, when stated in terms of wavelengths, is still very simple. If an electron acquires energy from light of wavelength λ (whether this light is part of a discontinuous spectrum or of a

continuous spectrum resolved by a prism or grating), then it acquires an amount of energy E_λ , given by

$$E_\lambda = 1234/\lambda \quad (1)$$

when E_λ is measured (as usual) in volts and λ in $m\mu$ ($1 m\mu = 10^{-7}$ cm.).

The following table gives a few wavelengths throughout the visible spectrum, together with the colours of the light to which they correspond roughly; the third column gives the corresponding value of E_λ —which will be called the “quantum voltage”—calculated from (1).

TABLE II

Colour	λ	E_λ
Extreme red .	750 $m\mu$	1.65 volts
Red . . .	650 ”	1.82 ”
Yellow . .	580 ”	2.13 ”
Green . . .	520 ”	2.37 ”
Blue. . . .	460 ”	2.68 ”
Extreme violet .	400 ”	3.08 ”

In order that light shall liberate electrons from a metal, that is to say, in order that it shall produce the photoelectric effect in that metal, the energy received by the electrons from the light must be greater than that which enables them to emerge. The wavelength of the light and the nature of the metal must be such that the quantum voltage of the light is greater than the work function of the metal; E_λ in Table II corresponding to the wavelength must be greater than ϕ in Table I corresponding to the metal. The wavelength such that the corresponding quantum voltage is equal to the work function of the metal is called the *photoelectric threshold* of the metal, and denoted by λ_0 ; since the quantum voltage increases as the wavelength decreases, the condition that there should be a photoelectric effect at all is that the wavelength of the light shall be less than the threshold of the metal. This may be called the **first law of photoelectricity**. The last column in Table I gives the threshold for the metals named therein. It appears at once that visible

light will produce no photoelectric effect in platinum, tungsten, or cadmium; for the thresholds of these metals are less than the wavelength of any visible light. On the other hand, the thresholds of the alkali metals, caesium, rubidium, potassium, sodium, all lie in the visible spectrum (or on the infra-red side of it), and all these metals will show a photoelectric effect with some visible light.

The thresholds of most other metals, none of which is known to have a work function greater than 10 volts, lie in the region of ultra-violet light, which is usually taken to extend from 400 to 100 $m\mu$. X-rays and γ -rays, which have still shorter wavelengths, produce the photoelectric effect, not only in all metals, but also in other solids and in gases, the work functions of which are even greater. Radiation of wavelength much longer than that of visible light produces no photoelectric effect.

If the quantum voltage of the light is greater than the work function of the metal, that is, if the wavelength is shorter than the threshold, the electron acquires more energy than is required for its emergence. The excess appears as kinetic energy of the electron after emergence. Accordingly, the speed of the electrons emergent from any metal increases as the wavelength of the light decreases. With visible light it can never be greater than that corresponding to an energy of a few volts; but with X-rays it amounts to thousands, and with γ -rays to millions, of volts.

The Magnitude of the Photoelectric Current.

Having decided in what conditions light will produce a photoelectric emission at all, we have now to inquire how great an emission it will produce. If every electron that took up energy from the light emerged from the metal, the answer to this question would be simple, at least for monochromatic light; we should simply have to divide the energy absorbed from the light by the energy taken by each electron, and the result would be the number emerging. But this hypothesis is very far from true. Even if an electron just below the surface takes up energy greater than the work function, it will not necessarily emerge; for its motion may be carrying it into the metal rather than out of it, or so as to make a glancing rather than a direct impact on the

boundary. The work function is not the energy that causes every electron to emerge—no amount of energy could secure that; it is the amount that enables the most favourably placed electron to emerge. Again radiation penetrates a finite distance into even the most opaque metals; the electrons receiving energy below the surface have to thread their way through many layers of atoms before they emerge, and in so doing they will lose much or all of their energy, even though they are not bound to the atoms. In the most favourable circumstances by far the greater part of the energy is absorbed by electrons that never emerge at all; this energy is ultimately communicated to the atoms and heats the metal. Lastly, if we are asking what emission is produced by a given amount of incident light, we must remember that some of the light will be reflected and will not be absorbed permanently by the electrons at all.

Accordingly, a calculation of the relation between photoelectric emission and intensity of incident light would have to take into account the penetration of the light into the metal, its reflection by it, and the loss of energy of the electrons in colliding with atoms. We do not know these factors sufficiently to make the calculation; and if we did, it is certain that the relation that would result from it would be extremely complicated.

But there is one simple law that follows directly from the theory of the photoelectric effect. Since each electron reacts effectively with a single electron in the source, the effects of several sources acting at the same time are independent and additive. If source *A*, acting alone, produce the emergence of *a* electrons per second, and source *B*, acting alone, the emergence of *b* electrons per second, then *A* and *B* acting concurrently will produce the emergence of $a + b$ electrons per second. That law is accurately and universally true, though—this warning is necessary—it may not be true of the currents that result from the emergence.

It has a very important consequence when we are concerned always with light of the same quality but different quantity. There are several ways (which we shall discuss presently) of defining quantity of light, but they all agree in two points: the photoelectric emission produced by two beams of the same quality and quantity is the same, and

the quantity of light in n similar beams is n times that in any one of them. It follows immediately that, if the quality is unchanged and the quantity alone varies, the rate at which electrons are emitted is proportional to the quantity of the light. This we shall call the **second law of photoelectricity**; it is accurately true; again a warning against misinterpreting it must be given.

Some Minor Points.

Although this chapter can offer nothing but the barest sketch of photoelectric theory, it would not be wise to leave wholly unmentioned some vagueness or even inconsistencies which the careful reader will have noticed. First, the second law follows strictly from the theory only if the light is monochromatic and is part of a discontinuous spectrum; for it is only then that the electron in the metal reacts with a single electron in the source. Nevertheless, it is true whatever the source; in photoelectricity the nature of the source is always immaterial, so long as the nature of the radiation is the same.

Next, a comparison of the accounts of thermionic and photoelectric emission might suggest that the threshold ought to depend on the temperature, and move to longer wavelengths at higher temperatures. As a matter of fact, the photoelectric effect is almost wholly independent of the temperature until temperatures are reached at which it is masked by thermionic emission; the variations at lower temperatures that have been reported (none are certainly established) are not of the kind that this argument would suggest, and are quite unimportant experimentally.* This independence of temperature was a puzzling mystery for a long time, and has only recently been explained. Briefly, the reason is that the electrons of which the energy varies with the temperature form a very small fraction of the whole at low temperatures; most of the electrons have an energy independent of temperature and nearly the same for all; the thermionic electrons are drawn from the small

* See H. E. Ives, *Journ. Opt. Soc., America*, viii, 551 (1924). H. E. Ives and A. L. Johnsrud, *Journ. Opt. Soc., America*, xi, 565 (1925). J. W. Hornbeck, *Phys. Rev.*, xxiv, 631 (1924). R. C. Burt, *Phil. Mag.*, xlix, 1168 (1925); *Phys. Rev.*, xxiii, 774 (1924); and *Phys. Rev.*, xxiv, 207 (1924).

number with energies varying about a mean that increases with temperature; the photoelectric electrons from those with constant energy. But the presence of the thermionic electrons does affect the threshold to a small extent; the threshold is not perfectly sharp; the emission does not stop perfectly sharply at a certain wavelength, but falls off extremely rapidly but asymptotically (see page 29). In the region where this rapid falling off occurs there is probably some dependence on temperature even when the thermionic emission is wholly inappreciable; but there the whole effect is so small that the change cannot easily be detected.

Finally, a word may be added about the photoelectric effect in non-metals. From the surface of these, and from their interior, radiation of sufficiently short wavelength can eject electrons; but since they are bad conductors, a current to a neighbouring electrode is not easily established. The effect of the radiation appears as an increase of conductivity of the material rather than as a current flowing from it. This is the ultimate principle of selenium and other *photo-conductivity* devices; but the primary action of light is complicated by many secondary changes that have not yet been disentangled completely.* Another electric action due to light, which may have practical uses, is a difference of potential arising between electrodes immersed in certain liquids when one is illuminated and the other not; here too the ultimate explanation must lie in the greater energy of the electrons on which the light falls. In fact, all actions of light, whether apparently electrical or not, must ultimately be due to the photoelectric effect, if they involve in any way the transference of energy from radiation to matter; for the acquirement of energy by electrons, subject to the laws that we have discussed, is the only manner in which the transference can take place.

* Our present knowledge of photo-conduction is largely due to the work of Gudden and Pohl; it is summarized well in Gudden's book mentioned in the note on page 11.

CHAPTER III

PHOTOELECTRIC EMISSION

Definition of Emission.

THE first and second laws enunciated in the previous chapter are the only contributions that pure theory can make at present to the practical problem of determining the relation of the primary photoelectric current to the light that produces it. The rest we must obtain from laws that are still wholly or partly empirical. But we may usefully employ the theoretical laws in stating the empirical laws. Thus, with the help of the second law, we may eliminate at once the quantity of the light from our consideration; for the law states that the ratio of the current to the quantity of light is independent of the quantity and dependent only on the quality; we shall concentrate our attention on the quality of the light by stating all the facts in terms of this ratio.

It is sometimes called the *sensitivity* of the cathode, for light of the quality concerned, and sometimes its *efficiency*; the first word is needed for another purpose, and the second is badly overworked already. Accordingly, we shall term the ratio of the primary photoelectric current to the quantity of light producing it the *photoelectric emission*, or simply the emission; it depends on the quality of the light and the nature of the cathode.

But our definition of the emission is not yet complete; for the term *quantity of light* is ambiguous. The quantity is sometimes measured by the power conveyed by the light (i.e. the rate at which it gives energy to a body that absorbs it totally), sometimes by the brightness, estimated visually, that it produces on a given surface on which it falls; and there are other alternatives of less importance. It is customary to adopt the first alternative, and to define the emission as the ratio of the photoelectric current from a given cathode to the power of the radiation of given

quality that produces it.* The basis of the custom is or was theoretical; it was expected that this definition would enable the experimental laws to be related to theory more simply than any other. It is not the definition that would suggest itself immediately to the user of photoelectric cells. For in practice the power of light and its quality are not independent variables, and equality in respect of power alone does not constitute equivalence in respect of any of the common uses of radiation. When we want to know how the current will vary with the voltage applied to an incandescent lamp, or in which of two cells the current is most nearly proportional to the visual intensity, independent of colour, a knowledge of the emission alone will not suffice; to answer the first question we must know also the radiative properties of tungsten; to answer the second we must know also the visibility curve of light. If photoelectric cells were confined to one particular use, some other method of characterizing quantity of light would certainly be preferable; but, as there is no other method that is any better suited to all of their manifold uses, translation of the facts will always be required for all uses but one, however they are expressed. The customary definition has the practical advantage that it provides a common language from which translation into the language appropriate to any particular use can be made with the help of existing data, for in all studies of radiation the energy or power is one of the magnitudes measured.

We shall therefore adopt it, with a warning that the expression of the facts by means of it is sometimes misleading at a first glance; later some of the facts will be stated again in a manner adapted to particular uses.

Incident and Absorbed Light.

But there is another ambiguity. The photoelectric current from a given cathode is not determined simply by the power and the quality of the incident radiation; it depends also on the mode of its incidence on the cathode. If by quantity of light we mean quantity of incident light, we must be pre-

* The usual practice is to express the emission thus defined in coulombs per calorie, or coulombs per erg. We prefer to express it in amperes per watt, partly because thermionic emissions are expressed in amperes per watt, and partly because the units are more familiar. 1 ampere per watt = 4.2 coulombs per calorie = 10^{-7} coulombs per erg.

pared to recognize that the quality of the light depends on its mode of incidence. In theoretical treatises the complication is met by defining the emission as the ratio of the current to the power of the radiation absorbed by the cathode, not to the power incident upon it. For in many circumstances the variations of the current with the mode of incidence are merely due to the variation of the reflecting power of the cathode; more current is obtained when the light is incident normally than when it is incident obliquely, because more light is absorbed and less reflected; if only light absorbed is reckoned in estimating the emission, then the emission is independent of the incidence. If this law were always true, and if perfect black-body cells (see page 8) were always used, this definition would also be useful practically. For if all the light incident on the window of a cell is absorbed at the surface of the cathode, and if the current is determined simply by the light absorbed, independently of how it is incident, then in such a cell the emission, estimated on the basis of light absorbed, would determine completely the current due to a given beam of light incident on the window. But such cells are not always used, and the law is not always true; moreover, the law fails for just those cathodes that are most important experimentally.

For practical purposes, therefore, we must define the emission in terms of the light incident on the cathode, or on the window of the cell, if this is smaller than the cathode; the emission will then be dependent on the mode of incidence. Even if we knew completely the relation between the emission and the angle of incidence of a parallel beam of light on a plane surface, it would be almost impossible to calculate from that relation the emission in any particular cell in any particular beam; for cathodes are not usually geometrically plane, and the light thrown on them is not usually a parallel beam; in practice it would still be necessary to measure the emission separately for each particular case. But, fortunately, the emission for actual cathodes does not vary very greatly with the mode of incidence; they have usually matt and not polished surfaces, so that the angle of incidence of a parallel beam varies widely over a small area, even if it is geometrically plane. The distribution of the varying angles of incidence on the differently inclined elements of

the matt surface does not change very greatly with the angle at which the light would be incident if the surface were optically plane, and it is found experimentally that changing the mode of incidence of the light on the cell within reasonable limits does not generally change the photoelectric current in a ratio of more than 2 to 1 so long as all the light reaches the cathode. Since, as we shall see, variations in the emission as great as this arise from circumstances even more difficult to control, it is permissible for our purposes to neglect the effect of the mode of incidence and to regard the emission, or the ratio of primary current to incident energy, as a characteristic of the cathode independent of the geometrical form of the cell and the way the light enters it.

But should not one exception be made, namely, the "black-body" cell in which light incident on one part of the cathode is reflected to another? If the reasons for which this type of cell was originally introduced proved in fact to be valid, the exception would have to be made; for it was expected that repeated reflections would increase greatly the primary photoelectric current due to a given beam of light. But these expectations are not fulfilled. It is difficult to estimate with any precision the increase in the primary current that results from adopting the "black-body" construction, because a change in the form of a cell may lead to changes in the nature of the cathode surface; when cells of different geometrical form are compared it is never certain that there is no difference in anything but form. But the comparison of many cells of widely different forms does not indicate that the primary current from cells of type *A* exceeds that from cells of other types receiving the same beam of light, or that there is any consistent difference in the relation between emission and wavelength.

Probably the reason is that the cathode absorbs strongly the light which excites the greater part of the current, so that the only light which suffers repeated reflections is that which has little photoelectric effect. The matter needs further exploration, but the facts are sufficient to show that for our particular purpose it is unnecessary to make a distinction between black-body cells and others, at least when visible light is used.

Variation of Emission with Wavelength.

The emission then is to be defined as the ratio of the primary current to the power carried by the beam of light that reaches the cathode. It varies with the quality of the light and, in particular with the wavelength; $\sigma(\lambda)$ denotes the emission for homogeneous light of a single wavelength λ ; we have to inquire how $\sigma(\lambda)$ varies with λ .

Some general laws concerning the variation of $\sigma(\lambda)$ with λ are shown diagrammatically in Fig. 2; it does not refer to any particular cathode, and only shows the orders of the magnitudes concerned. For most metals $\sigma(\lambda)$ is given by a curve similar to *A*, decreasing as the wavelength increases. Such a curve, taken alone, does not suggest the existence of a definite threshold at which the emission becomes definitely zero; and, indeed, it is impossible to define the threshold precisely by measurement of the emission. Its position is usually determined either by working with a continuous spectrum and extrapolating an approximately linear part of the curve as it approaches the axis, or by working with a discontinuous spectrum and noting the last line for which some current can be detected. Indeed, evidence for the existence of a definite threshold is theoretical rather than experimental. It is confirmed by measurements of the initial velocity of the electrons, which are not of sufficient importance for our immediate purpose to require mention here; but, because it is so difficult to fix experimentally, and for another reason that will appear presently, all values assigned to thresholds (e.g. those of Table I) are subject to considerable uncertainty.

Curve *A* cannot rise indefinitely to the left; for there is a definite value that the emission cannot exceed, namely, that attained when every electron taking energy from the light emerges and contributes to the saturation current. According to (1), each electron takes an amount of energy $1234/\lambda$ volts, or $1234\varepsilon/\lambda$ watt-seconds, where ε is the charge on an electron in coulombs; consequently, if light carrying power W is completely absorbed for a time t , $n = Wt\lambda/1234\varepsilon$ electrons must take energy from it. If all of these emerge, they will give a primary current $i = n\varepsilon/t$ amp.; $\sigma(\lambda) = i/W$ will be $\lambda/1234$ amp. per watt. This

maximum possible value of $\sigma(\lambda)$ decreases with λ as shown at the top of Fig. 2; the curve of $\sigma(\lambda)$ cannot rise beyond its

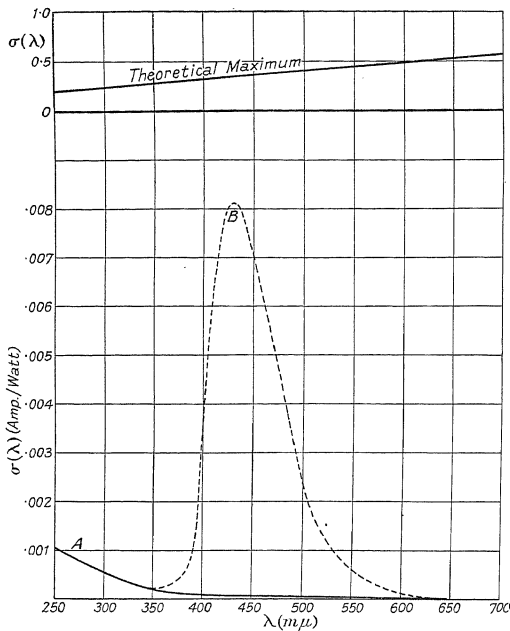


FIG. 2. TYPICAL EMISSION CURVES

intersection with this line. Probably it never rises nearly so far; but its maximum lies in the region between ultra-violet and X-rays, which is peculiarly inaccessible experimentally, and has never been traced; in the region of ordinary X-rays,

the maximum has been passed, and $\sigma(\lambda)$ decreases with λ . In the region shown in Fig. 2, with which we are concerned, very few absolute measurements have been made; most experimenters content themselves with determining the relative values of $\sigma(\lambda)$ for different wavelengths; but no value as great as 1 per cent of the maximum possible seems to have been recorded when the curve is of form *A*, so that no question of an approach to the maximum arises.

But though curve *A* is characteristic of most metals, it is not characteristic of those of greatest photoelectric importance. Metals of which the threshold lies in the visible or infra-red give curves of form *B*, in which a relatively enormous hump is imposed at one part on the steady fall with increasing wavelength; at the peak of this hump the emission may be as much as 3 per cent of the theoretical maximum. The presence and magnitude of this hump depend intimately on the mode of incidence of the light. It is completely absent if the surface of the cathode is optically plane and the light is incident normally, or if the light is incident obliquely, but is plane-polarized with the electric vector parallel to the surface; it appears only if the electric vector has a component perpendicular to the surface. (The electric vector is parallel to the short diagonal of a Nicol prism which transmits the polarized light.) Moreover, though similar changes of the emission with the angle of incidence and state of polarization occur with metals that give curves of form *A*, and outside the hump of those which give form *B*, these changes are, as we saw, associated with changes in the reflecting power; the emission, reckoned on the basis of power absorbed, is independent of the mode of incidence. But within the hump the changes cannot be accounted for wholly thus; they persist even when emission is reckoned on the basis of absorbed power.

Accordingly, there is a difference in kind and not merely in degree between emission within the hump and emission outside it or in its absence; the former is said to be "selective" (since it only occurs within a narrow range of wavelengths), the latter "normal." The particular feature that is used to distinguish these two kinds of emission, namely, the effect of the plane of polarization, is not of practical importance; for when the surface of the cathode is matt and

not optically plane, the electric vector of the light always has a component perpendicular to the surface, whatever the nominal angle of incidence or the state of polarization; the hump is always present if the metal is one capable of selective emission at all, and curves of form *B* are as definitely characteristic of some cathodes as curves of form *A* are of others. In the use of photoelectric cells it is not necessary to know whether the emission that is being used is normal or selective; but actually, when visible light is employed, it always is largely selective. For it is only within the humps of curves of form *B* that the emission of any metal under visible light is large enough to be practically useful; if we confined ourselves to normal emission—and some difficulties would be avoided if we could do so—we should have also to confine ourselves to ultra-violet light.

Variation of Emission with the Cathode.

Such are the general laws of the variation of $\sigma(\lambda)$ with the quality of the light. There are also some general laws of its variation with the nature of the cathode. The thresholds of metals that are highly reactive chemically lie generally on the red side of the thresholds of relatively inert metals. Among metals that give only normal emission, it appears (but the evidence is very incomplete) that the curves relating $\sigma(\lambda)$ and λ seldom cross each other, so that the metal with the greater threshold (i.e. threshold at the greater wavelength) has the higher emission at all less wavelengths within the bounds of Fig. 2. As we pass from one "normal" metal to another, the curve of $\sigma(\lambda)$ moves parallel to the horizontal axis nearly unchanged in form; though the threshold cannot be determined precisely, it has experimental as well as theoretical importance, because it fixes the position of the whole curve. Among metals with selective emission, the peak of the hump moves generally with the threshold, and lies at longer wavelengths for the metal with the greater threshold; the change from one metal to another again produces a shift of the whole $\sigma(\lambda)$ curve; but there is also a change of form. This is illustrated in Fig. 3, which represents the emission of certain cathodes of the alkali metals, sodium (Na), potassium (K), rubidium (Rb), and caesium (Cs); these are named in the order of increasing chemical

activity and increasing threshold. It will be seen that the curves may cross each other, and the cathode with the

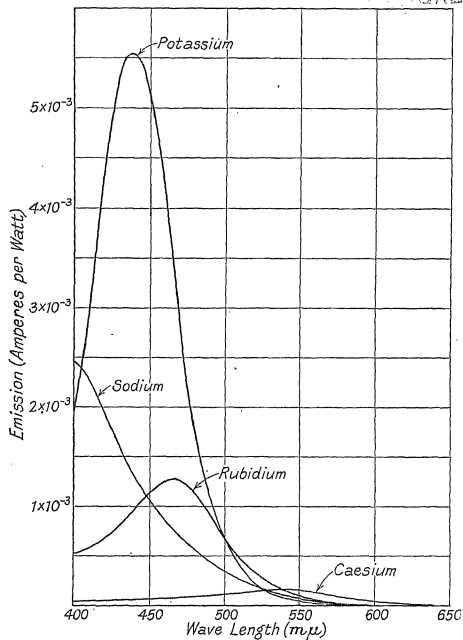


FIG. 3. AVERAGE EMISSION CURVES OF ALKALI METALS

greater threshold may have a lower emission at shorter wavelengths; the emission is no longer fixed completely by the threshold.



Effect of Gas Films.

But all such general laws are greatly complicated by a circumstance to which close attention must be paid. The photoelectric effect is a surface effect, and the emission from a cathode is not determined merely by the chemical nature of the metal forming the bulk of it, but is modified profoundly by the condition of its surface. In particular, all solid surfaces, even in the best vacuum that can be produced, are covered with a layer of adherent gas, unless extremely rigorous measures have been taken to remove it; the emission depends quite as much on the nature of this layer, which may be only a few atoms thick, as on the nature of the substance to which it adheres. The emissions of Fig. 3 are not those of perfectly clean surfaces of the metals named; they are those of the metals covered with such adherent layers as are likely to form when the metals are prepared by one particular method ("sensitization," see page 34); if the same metals were made into cathodes by some other process, the emission might be greatly changed.

This effect of adherent gas is the subject of an enormous literature, but the facts are by no means yet beyond dispute. A great part of the outstanding discrepancies between the results of different experimenters doubtless arises from differences in the nature of the gas layers with which they have dealt. For it is very difficult to control the layers or to ascertain their exact nature. Experiments on this matter usually consist in removing the layers by long-continued heating or by repeated distillation in a very high vacuum or by exposing the uncontaminated interior by scraping, and in noting the resulting change in the emission; it is never certain that the layer has been removed and not replaced by another, and, if it were, the nature of the removed layer would still be doubtful. But two facts seem to be clearly established. First, the removal of the layers ordinarily adherent to chemically clean surfaces of metals giving normal emission decreases the threshold and with it the emission throughout the ultra-violet region; by sufficiently drastic treatment such metals can be made almost completely insensitive within the range of Fig. 2. Second, the selective emission from the alkali metals can be abolished entirely by

the removal of gas; the threshold is not greatly changed, but the abolition of the selective emission makes them practically insensitive to visible light; possibly an even more complete removal would decrease the threshold.

The presence of adherent gases is, therefore, not harmful as might seem likely at first sight, but highly beneficial. Most of the activity of almost all the metals used in photoelectric cells, within the spectral range for which they are intended, is due to the presence of gas films on their surface; if perfectly clean surfaces of chemically pure metal could be produced they would be worthless for practical purposes. It is not known whether all gases are beneficial; but if they are not, it must be regarded as a fortunate coincidence that the gas which adheres when cathodes are prepared by convenient processes (such as distillation of the metal in an evacuated vessel) is of the beneficial kind. On the other hand, it is not wholly fortunate that adherent gases are required at all. For though the complete removal of gas is a troublesome and laborious business, it would at least lead to the same result every time; if this were our ideal, photoelectric cells might be expensive, but they would be uniform. But when some gas has to be left adherent, it is impossible to ensure that the gas left is the same in every cell; cells prepared by apparently the same process cannot be expected to have exactly the same emission.

And there are, in fact, very considerable differences between such cells, as has been hinted already. Fig. 4 shows the emission curves of a batch of 8 cells (sensitized potassium) prepared in exactly the same way; their emissions for the same wavelength sometimes differ by as much as 2 to 1, even in the neighbourhood of maximum emission. Nevertheless, there are marked regularities. The wavelength at which the emission is a maximum varies little; the relative variation is least on the short wavelength side, and greatest in the neighbourhood of the threshold. In general, the difference between cells intended to be similar is not so great as to mask the difference between those intended to be dissimilar. The regular change in the emission curve throughout the series of alkali metals, shown in Fig. 3, is not entirely delusive. If the curves for a large number of cells of each metal had been included in that figure, the change from one

metal to another would have been partially obscured, but certainly not entirely, especially if the cells were all of the same form and were prepared in the same manner so far as the varying properties of the metals permit. We cannot speak accurately of the emission of (e.g.) potassium, but we can speak reasonably of the average emission of a group of

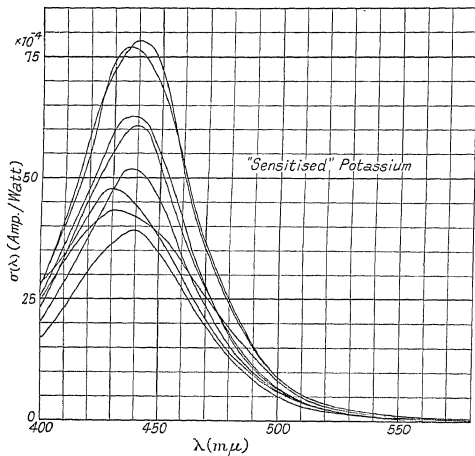


FIG. 4. EMISSION CURVES OF EIGHT SIMILAR CELLS

cells containing that metal prepared in a certain manner, and distinguish it from the average emission of cells containing other metals. On the other hand, small changes in the form or method of preparation will induce surprisingly large variations in the average result.

Sensitized Metals.

The gas that we have considered so far is that which adheres naturally to the metal in the course of the

construction of the cell. The question naturally arises whether by introducing a small quantity of suitable gas intentionally we cannot improve the emission. No useful process exactly

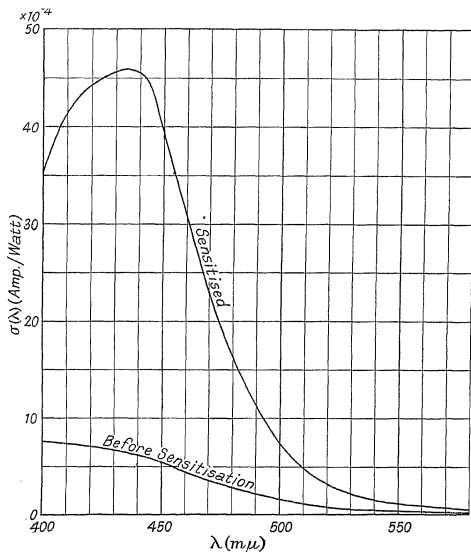


FIG. 5. CHANGE IN EMISSION DUE TO "SENSITIZATION"

of this nature seems to be known; the introduction of a small quantity of oxygen or water vapour into cells containing potassium (and probably other alkali metals) increases temporarily their emission at the longer wavelengths, but the effect decays, probably owing to diffusion of the gas into the interior of the metals, and leaves little permanent change. But a process is widely employed that probably derives part

at least of its virtue from the formation of a gas film. Surfaces of potassium are usually "sensitized" by filling the cell with hydrogen at a pressure of a few millimetres, and passing an electric discharge for about a minute through the gas with the potassium as cathode. The result is to shift towards longer wavelengths the threshold and the wavelength of the maximum of the selective effect, and to increase the emission generally. Fig. 5 shows the change in one experiment. Changes of the same nature are produced by the same process in the other alkali metals, though not so far as is known in metals of other groups; but the magnitude of the changes decreases generally as we pass from sodium to caesium. The conditions for the maximum change have to be ascertained for each cell, but there are wide limits within which alteration of the pressure of the gas, and of the duration, and of the current carried by the discharge, make little difference. The exact effect of the process is not known; it has been variously interpreted as the formation of a hydride of potassium and of a colloidal modification. The first interpretation is certainly wrong, although cells treated in this manner are still often called potassium hydride cells; the second dates from a time when the great influence of gas layers was not known. Part of the change is probably optical; for the colour of the surface is changed and its absorption of light increases; the surface becomes bluish in place of silvery or (if the metal has been deposited from vapour and is finely divided) pure grey. But part is almost certainly due to the formation of a surface layer of hydrogen.

Thin Films of Photoelectric Metals.

Quite recently a new method of using the alkali metals to produce photoelectric cathodes has been introduced, which may in time replace all existing methods.* It depends again on the fact that the photoelectric emission is a surface and

* Work on the photoelectric properties of thin films of the alkali metals was started by H. E. Ives, *Astrophys. Journ.*, lx, 209 and 231, 1924; lxii, 309, 1925; lxiv, 128, 1926. *Journ. Opt. Soc., America*, xii, 486, 1926. For their practical application see L. R. Koller, *General Electric Review*, xxxi, 476, 1928; and N. R. Campbell, *Phil. Mag.*, vi, 633, 1928. A paper on caesium films by K. T. Bainbridge is promised by Koller, but had not appeared in time for mention here.

not a bulk effect. We noted in Chapter I that glass exposed to the vapours of the alkali metals becomes coated with a

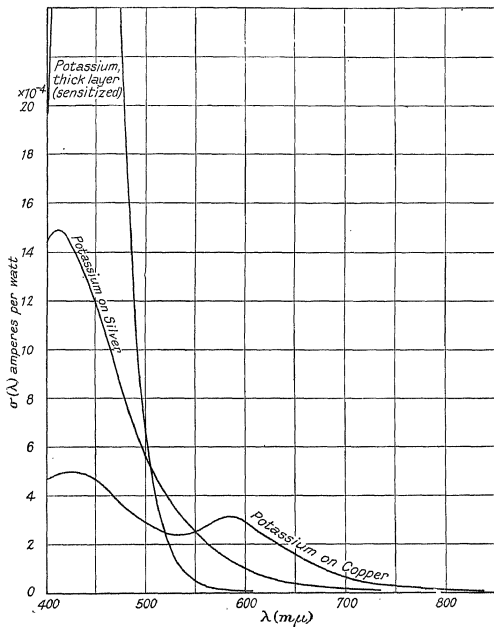


FIG. 6. EMISSION OF THIN FILMS OF POTASSIUM

thin film of them. The conductivity of this film, though large enough to cause trouble when high insulation is required, is not large enough for the purposes of a cathode intended for moderately large illuminations; but similar

films are formed on metallic surfaces exposed to the vapours, and can be supplied with current from the underlying conductors. These thin films possess a characteristic emission quite different from that of the metal of which they are composed when in bulk, and determined by the underlying

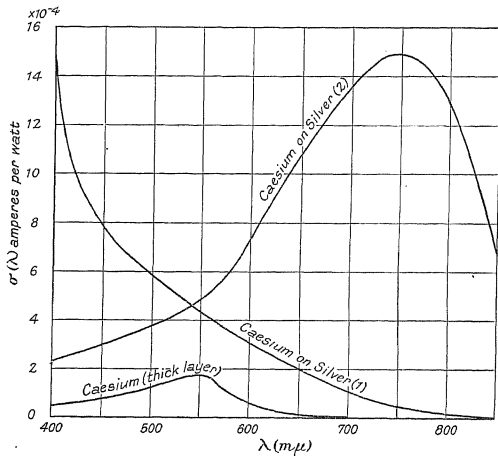


FIG. 7. EMISSION OF THIN FILMS OF CAESIUM

material as well as by gas deposited on that metal or on the thin film. They seem always to have a greater threshold than the bulk metal, and sometimes a second maximum in their emission curves at a longer wavelength than the normal maximum. It is not known yet whether this second maximum is a selective emission, in the sense of varying with the plane of polarization.

Two examples of the difference between thin and thick films are shown in Figs. 6 and 7, referring respectively to potassium and caesium. It will be seen that while a thin

film of potassium on silver, not intentionally oxidized, merely shows a shift of the threshold to the red, a thin film of the same metal on oxidized copper shows a second maximum. The thin film of caesium on oxidized silver is even more remarkable, for the maximum characteristic of the thick metal has wholly disappeared. In form (1) it has possibly been displaced to shorter wavelengths, and in form (2) towards longer wavelengths. Forms (1) and (2) differ in the precise treatment of the silver before the deposition of the caesium and of the resulting film after its deposition; but the exact nature of the changes that produce such different results is not known. Forms intermediate between (1) and (2) and possessing two maxima can be produced, but consistency in reproducing the same form by apparently the same treatment is the exception rather than the rule.

The study of these thin films has begun quite recently; the theory and the facts are still uncertain, and the statements made here may need correction by the time that they are in print. But it is impossible to omit all reference to the matter, for it is clearly of the greatest importance in the practical use of photoelectric cells. They can now be used in regions of the spectrum that were wholly inaccessible to them a short while ago; and it is by no means unlikely that cathodes of the new type will displace those of the old type even in the regions accessible to them.

Changes of Emission During Use.

We must now turn to a different aspect of the facts with which the preceding sections have been concerned. The earlier workers on photoelectricity were greatly concerned with a phenomenon that they called "fatigue"; the emission from their cathodes under a constant illumination and field continually diminished as they observed it. There was a great conflict of evidence whether this fatigue occurred only when the light fell on the cathode, or whether it occurred equally in the dark; as usual, it is now known that both groups of disputants were right, and that both kinds of "fatigue" may occur. But it is clear also that the term *fatigue* is inappropriate. The changes have no analogy, as seems to have been supposed at first, with the decay of the light of phosphorescence after the exciting illumination is removed. Even if

they depend on illumination they are never the direct result of it, but are due to alterations in the cathode produced by secondary and inessential actions. The term is still widely used; but it is better to abandon it, and to speak merely of changes in the emission of the cells*

The changes may be due to various causes. In the original observations they were due, at least in part, to an oxidization of the cathode by the air to which it was exposed. Such changes due to ordinary chemical reactions, and quite independent of illumination, are of no importance in modern sealed cells; all such reactions are completed before the cell is taken into use. They may also be due to the formation of the gas films already mentioned (pp. 30-32); or to accumulation of charges on the walls which alter the distribution of the field. Illumination may produce a change of this kind; for, if the cell is exposed to a strong incandescent source, the walls may be heated appreciably and the distribution of the film or of the charges changed. Lastly, they may be due to alterations in the surface film on the cathode, which so largely determines its emission. Here again the mere heat from the source may cause the changes; but they are more often associated with the impact of positive ions on the cathode. They will occur in the dark, if the potential applied to the cell is sufficient to cause a glow discharge; but, when the cell is illuminated, they will occur at lower potentials, and, indeed, at any potential at which there is sufficient ionization by collision to produce an appreciable magnification of the primary current.

Changes of this last kind, which are much the most serious, can only occur if gas is present in the cell. In a well-made vacuum cell the emission is very constant; a variation of 1 per cent in the current produced by any small illumination ought not to be tolerated; it usually indicates imperfect evacuation, probably due to the liberation of gas after sealing from the pump. But such variations may occur in very strong illuminations, and be due to heating of the walls or of the cathode. Here cells of type *C* (central cathode) are somewhat less satisfactory than other types, because the thermal insulation of the cathode is nearly perfect, and a

* The most complete investigation of "fatigue" is that of H. Rosenberg, *Zeit. f. Phys.* vii, 18, 1921.

comparatively weak radiation may produce a considerable rise in temperature. On the other hand, few, if any, cells are wholly free from change of emission when illuminated;

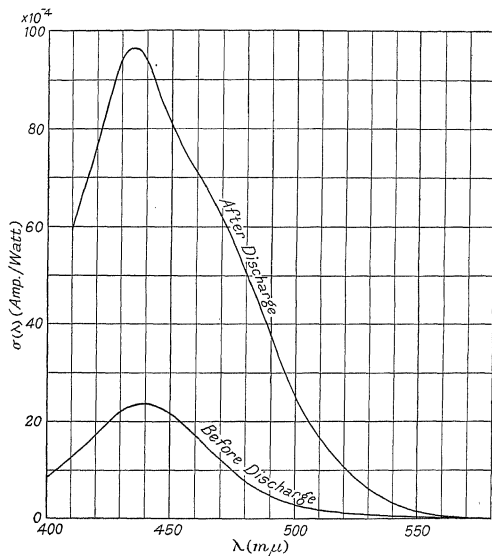


FIG. 8. INCREASE IN EMISSION DUE TO PASSAGE OF GLOW DISCHARGE

in the compensation methods of page 113, when a change of 1 part in 10,000 in the current can be detected, it is rare to find a pair of cells that will give a balance wholly free from a drift, which shows that the current from one cell is increasing relatively to that from the other. The cause of this drift has not been established certainly; but it is

probably due partly to changes of temperature, partly to the residual gas that is present even in the most perfectly evacuated cells.

In gas-filled cells, especially when voltages near the glow potential are applied in order to obtain high magnification, the changes are much more serious. In all such cells the current under a given illumination depends somewhat on the previous history. The changes are least serious when the cathode is relatively free from adherent gas, having been prepared by simple distillation of the metal in a vacuum, and when the cell is filled with inert gas; then even the passage of a glow discharge does not alter materially the emission or the current at low voltages. But even then there will be changes at higher voltages, the origin of which is uncertain. If a voltage giving considerable magnification is applied, and a series of illuminations thrown on the cells in a regular cycle, the same currents will not be obtained in the first few repetitions of the cycle. If it is repeated often enough, a constant relation of current to illumination will be obtained; but this relation will vary with the range of the cycle and with the time occupied in traversing it.

When the cathode has been sensitized and the cell filled with inert gas, the passage of a glow discharge after the cell has rested for some hours produces a large increase, sometimes as much as 5-fold, in the emission measured at low voltages, together with some change in the form of the emission curve. Fig. 8 shows this change in one particular cell. If a voltage just below the glow potential is applied, this change of emission will occur gradually, and the variations in a cycle will be very large.

CHAPTER IV

PHOTOELECTRIC DATA

Selection of Data.

EMISSION curves, such as those given in the preceding chapter, contain all the information necessary to choose, from among the cathodes to which they refer, that which will give the greatest primary photoelectric current in any particular circumstances. But the information is not in a convenient form; the purpose of this chapter is to translate it into a form adapted to practical needs.

First we must decide what cathodes are to be considered. Most of the cells offered for sale have cathodes of sensitized potassium; but some makers offer also sodium, rubidium, and caesium cells, presumably sensitized, except possibly in the case of caesium, which is little affected by sensitization. In addition, cathodes of the thin film of potassium on oxidized copper and of caesium on oxidized silver (form (1) of page 36) are available. (Cathodes of caesium on oxidized silver resembling more nearly form (2) have become available since this chapter was written. Representative data cannot be given yet, but these cathodes have considerably greater emission for white light than any of those discussed below, and very much greater emission for light of long wavelength.) All these are intended for use with visible light. Cells provided with quartz windows, intended for use with ultra-violet light, have cathodes of sodium, lithium, or cadmium. To these we shall confine our attention. As has been indicated already, the development of other thin film cathodes may change the position completely in the visible region; and the possibilities of barium and strontium must not be overlooked.* When the measurements in the ultra-violet that are urgently needed have been made the position may be changed there also. But at the present time

* Information on the photoelectric emission of Ba and Sr is to be found in: R. Pohl, *Elster u. Göttinger Ann.*, 192, 1915. T. W. Case, *Phys. Rev.*, xvii, 398, 1921; xviii, 413, 1921. R. Döpel, *Zeit. f. Phys.*, xxxiii, 237, 1925. See also British Patents, 178300 and 178301.

it is impossible, and would be useless, to consider these possibilities.

Next we have to face the difficulty arising from the variability of the emissions from cathodes intended to be identical. The data that we give are intended to refer neither to the very best cathode of each type that it is possible to produce nor again to the worst that is likely to emerge, but to the best average that seems likely to be attainable in production on a considerable scale. An individual cell may give as much as twice the emission that we prescribe, and if it gives only half that emission it is not to be rejected as hopelessly bad. The emission is supposed to be measured after the cell has had a long rest; no account is taken of the large increase in the emission which may follow a discharge, or the incidence of powerful lights, in gas-filled cells (page 40).

In estimating this average we have had to rely largely upon our own measurements, except for the caesium on silver cathodes.* In the scientific literature little relevant information is to be found; the emission curves usually give only the relative and not the absolute values of $\sigma(\lambda)$. When absolute values are given, there is often no evidence that they refer to a practical type of cathode, or the values offered are inconsistent with each other and with information derived from other sources. Lately, however, makers of photoelectric cells have begun to give detailed information concerning their performance. Here, again, the emissions claimed for cathodes of the same type vary over a very wide range; and (in our experience) the correlation between what a maker claims and what he achieves is by no means perfect. It would be tedious and out of place in such a book as this to set out in full the evidence on which our data are based; we have examined some hundreds of cells made in the institution to which we belong, and nearly a hundred cells made by others; and we have analysed all the published data that we can find. We have compared and correlated this information to the best of our ability, and offer our conclusions for what they are worth. If they

* The statements about thin films of caesium are based on Koller's paper, mentioned in the note on page 34, supplemented by private information from the author, to whom we are deeply grateful. Inspired by this information, we have repeated some of his experiments, and the curve for caesium form (2) in Fig. 7 is derived from our own measurements.

are shown to be untrustworthy, nobody will be better pleased than ourselves; for any proof of that kind must be based upon more extensive evidence, which is lacking at present, but badly needed.*

White Light.

In most applications of photoelectric cells they are exposed to light suitable for general illumination, such as daylight or the light from electric incandescent lamps. Such lights, though they would all be termed popularly white light, differ very widely in colour; and in order to give precise data the quality must be specified more nearly—even though “precision” in photoelectric data is consistent with a possible uncertainty of at least 50 per cent. We shall choose the light from a gas-filled incandescent lamp of moderate power (say, 100 watts), and this light we shall take to be similar in quality to that from a black body at a temperature of $2,650^{\circ}$ K. This is the light most important in practice; for cells are generally used with artificial sources of light, and, when choice is possible, this source is almost always chosen, because it best combines power and convenience.†

We might give the emission for light from this source, as usual, in amperes per watt. But since light suitable for general illumination is usually measured visually in lumens rather than in watts, it is more convenient to give the emission in amperes per lumen. If $P(\lambda, T)$ is Planck's function for temperature T , and $v(\lambda)$ is the visibility (i.e. lumens per watt)

* How scarce is trustworthy evidence appears clearly from Gudden's treatise (Chap. II, Note 1). The measurements of E. Seiler, *Astrophys. Journ.*, lii, 129, 1920, are often quoted, but it is to be observed that the cells she used were gas-filled; there is no evidence that the magnification (see Chap. VI) was the same in all of them. Moreover, though we do not doubt that her measurements of her own cells were accurate, we are not sure that they are representative; certainly they are not always concordant with our own measurements on a very much larger number of cells.

† Very full tables of the radiation properties of tungsten are given in *General Electric Review*, xxx, 310, 354, and 408 (1927). From these all information can be obtained concerning the variation of the quantity and quality of radiation from vacuum tungsten lamps with the temperature of the filament, and with current and voltage. The relation between temperature and radiation in a gas-filled lamp is very nearly the same as in a vacuum lamp, though a slight difference arises from the use of spiral filaments in gas-filled lamps. But the relation between current or voltage and radiation is more complex and depends on the exact construction of the lamp.

of light of wavelength λ , the emission measured in this way will be given by

$$\Sigma = \frac{\int_0^{\infty} \sigma(\lambda) P(\lambda, T) d\lambda}{\int_0^{\infty} v(\lambda) P(\lambda, T) d\lambda} \quad (2)$$

We thus find for our selected cathodes—

				Gas-filled Lamp ($T = 2650^{\circ}$ K.)
Sodium . . . . .	.	.	.	5.0×10^{-7} amp./lumen
Potassium . . . . .	.	.	.	10 "
Rubidium . . . . .	.	.	.	4.4 "
Caesium . . . . .	.	.	.	1.7 "
Potassium on copper oxide . . . . .	.	.	.	8 "
Caesium on silver oxide . . . . .	.	.	.	12.5 "

But a word should be said also about another source of white light, namely, the sun. The quality of sunlight is often assumed to be that of the light from a black body at 6,000 K.; and so far as the visual quality is concerned the assumption is doubtless true. If it were also true of the photoelectric quality, the emission for sunlight could be calculated from that for lamplight by means of the emission and visibility curves. According to such a calculation the emission of a potassium cathode for sunlight, estimated in amperes per lumen, should be about six times its emission for lamplight; and the ratio of the emission of a sodium cathode to that of a potassium cathode should be about twice as great in sunlight as in lamplight. But our experiments do not confirm these calculations. They show that the emission of potassium in sunlight is not more than twice its emission in lamplight, and that the ratio of the emission of sodium to potassium is rather greater in lamplight than in sunlight. The reason for this discrepancy is doubtless that the shorter wavelengths play little part in determining the visual quality but a great part in determining the photoelectric quality. This matter, like so many others connected with the emission, requires further investigation, but meanwhile it seems that no very great error will be made if the emissions of the foregoing table are applied to sunlight as well as to lamplight.

These figures enable the current to be expected in various

circumstances of frequent occurrence to be calculated easily. Thus if S is the effective area of the cathode placed at a distance r from a source emitting L_0 lumens (and of dimensions small compared with r), the lumens falling on the cell are given by

$$L = L_0 S / 4\pi r^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and the photoelectric current by $i = \Sigma L$. When there is no obstruction between cell and lamp, S is the area of the cathode projected on a surface perpendicular to the line joining it to the source; when the light is limited by a diaphragm (such as a window of the cell), S and r must, of course, refer to the diaphragm; when a simple lens is interposed to concentrate the light on the cathode, S and r refer to the lens. If the lamp is rated in candle-power and not (as is usual nowadays) in lumens, (2) can be used, if it is remembered that a lamp of C mean spherical candle-power emits $4\pi C$ lumens. If the lamp, being a gasfilled incandescent lamp of the type specified, is rated in watts, it may be taken as emitting 12 lumens per watt consumed. (In a gas-filled lamp the watts radiated are notably less than the watts consumed; the lumens per watt radiated are 15.7).

On the other hand, when the cathode of area S is exposed to diffused light (e.g. daylight) which produces an illumination I at its surface, of which the value, expressed in foot-candles, metre-candles (or lux) or phots, is known, the appropriate formula is

$$i = \Sigma SI. \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where S is in square feet if I is in foot-candles, in square metres if I is in metre-candles, in square centimetres if I is in phots.

Homogeneous Light.

When the light is of a single wavelength, all that matters is the value of $\sigma(\lambda)$ for that wavelength; the relevant facts are given sufficiently by the emission curves of the previous chapter. But it may be convenient to summarize the information in the following table in which the visible spectrum is divided into sections; for each section the cells having appreciable emission in that section are named, together

with their average emission within it. It is sufficient here to give the emission in amperes per watt; for though the power likely to be available is very different in different ranges (e.g. it is much easier to obtain light of high power at long wavelengths than at short), the relative intensities of sources at a given wavelength are the same whether the intensities are measured in watts or lumens or in any other manner.

RANGE OF SPEC- TRUM λ ($m\mu$)	MEAN VALUE OF $\sigma(\lambda) \times 10^4$.					
	Sodium	Potas- sium	Rubi- dium	Caesium	Potassium on Copper	Caesium on Silver
400-450	13	42	8	0.6	5	10
450-500	7	30	11	1.0	3.8	6.9
500-550	2	2.5	3.2	1.5	2.7	5.1
550-600	—	0.3	0.5	1.0	2.9	3.6
600-650	—	—	—	0.3	2.4	2.5
650-700	—	—	—	—	1.3	1.6
700-800	—	—	—	—	0.4	0.5

Corresponding facts for the ultra-violet do not seem to be known; very few absolute measurements of emission have been made. It is probable that for wavelengths between 400 and 300 $m\mu$, lithium has at least as great an emission as any other metal. Sodium has also a large emission, rising to a maximum in this region. For wavelengths from 300 $m\mu$ to 250 $m\mu$, cadmium, zinc, and silver have been recommended, but their emission is probably less than that of lithium. Below 250 $m\mu$ most metals have some emission, but no absolute values are known. It must be remembered that most of the ordinary glasses begin to absorb light at about 340 $m\mu$ and absorb strongly at 300 $m\mu$; cells for use in the further ultra-violet must have windows of quartz or be made wholly of that material. Glasses partially transparent to the ultra-violet are available, but none are as transparent as quartz and none are materially easier to use.

Selective Light.

A rather different problem arises when we want a cell that is sensitive to some radiations and insensitive to others.

Examples of such a problem are titration by means of indicators (page 201), infra-red signalling (page 200), or radiation therapy (page 181). If ideal light filters were available that would transmit perfectly a narrow band of the spectrum and absorb all other wavelengths, the problems would be reduced to that of the last section. We should choose a cathode which has a high emission where sensitivity is required, and cut out any other radiation by filters. But they are not; filters are available transmitting only narrow bands, but they always absorb to some extent even at the wavelength of their maximum transmission. It may be better to use a cathode with a marked maximum of emission in the desired region without a filter, or with a less dense but less selective filter, than a cathode giving a greater emission in the region, but with strong emission elsewhere that has to be suppressed by a highly selective filter, which is necessarily dense even in the region that it selects.

The solution of the problem, therefore, demands the consideration of possible filters as well as of possible cells, and a discussion of it would lead us too far afield. In respect of cells we will merely record that the following cathodes have marked maxima of emission (in amperes per watt) near the wavelengths stated.

Lithium	.	.	.	.	.	315? $m\mu$ *
Sodium	.	.	.	.	.	340
Potassium	.	.	.	.	.	440
Rubidium	.	.	.	.	.	480
Caesium	.	.	.	.	.	560
Potassium-on-copper oxide	.	.	.	.	.	420 & 600
Caesium-on-silver oxide	.	.	.	.	.	360

It is to be noted that there are no maxima of emission (which are usually characteristic of selective emission) beyond 300 $m\mu$.

For information concerning filters, reference should be made to other sources.†

* The values given for the maximum emission of lithium vary from 390 to 315 $m\mu$.

† The Kodak catalogue of Wratten filters gives complete information about filters of dyed gelatine films. Other useful information is to be found in papers: T. M. Dahm, *Journ. Opt. Soc., America*, xv, 266 (1927); E. Pettit, *Astrophys Journ.*, lxvi, 43 (1927); L. G. Jones, *Journ. Opt. Soc., America*, xvi, 259 (1928). See also A. Hübl, *Die Lichtfilter*, Knapp, Halle (1927).

But of one problem a little more may be said. It is sometimes desirable that the cell should be as sensitive as possible to ultra-violet light, but wholly insensitive to visible light. Zinc, silver, and cadmium are then suitable. The cadmium cell has received a good deal of attention, though for a reason

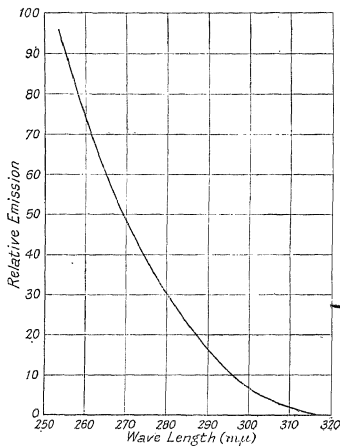


FIG. 9. RELATIVE EMISSION OF CADMIUM CELL

that does not seem to us entirely valid (page 183). Its emission curve is shown in Fig. 9, but the ordinates give merely relative values. The absolute values in amperes per watt are not accessible; but as a rough indication of the currents obtainable it may be stated that, if the entire radiation from a low pressure mercury arc carrying 4 amp. at 80 volts were received on a cadmium cathode, the resulting primary photoelectric current would be about 5 microamperes. But, of course, the figure depends considerably on the efficiency of the mercury arc lamp, and the distribution

of radiation throughout its spectrum ; these are very variable quantities.

Emission and Visibility.

A special and most important example of the preceding problem occurs in photometry, or the measurement of the visual effect of light. From the fuller discussion in Chapter XIII it appears that a cell will not be completely satisfactory for photometry unless its emission curve has exactly the same form as the visibility curve of radiation for the normal eye, that is to say, the curve giving the ratio of the lumens to the watts carried by radiation of given wavelength. This curve is shown in Fig. 10, together with the emission curves of some photoelectric cathodes ; since we are concerned only with the change of the emission or the visibility with wavelength, the maximum value on each curve is taken as unity.

It is clear that no cell known at present is quite satisfactory when this test is applied, though caesium is a good approximation ; nor can the requirement be met completely by the aid of filters, unless possibly they are so dense as to leave very little effective emission. But, in truth, there is no need to meet the requirement at all completely, because it is never necessary to compare accurately lights of very different colour. The conception of a luminous flux wholly independent of colour is artificial and of little practical importance ; the eye cannot really compare illuminations of very different colour, and in practice the utility of illumination depends almost as much on its colour as on its intensity. The real problem is to compare lights of not very different colour, and, in particular, those from electric incandescent lamps, which are the only sources in general use sufficiently constant to justify the use of the precise methods of photoelectric photometry.

The light from such lamps is always closely similar to that from a black body at some temperature between $2,000^{\circ}$ K. and $3,000^{\circ}$ K. ; within this range that between $2,300^{\circ}$ K. and $2,700^{\circ}$ K. is especially important, for it includes all tungsten lamps used for domestic lighting. A good test of a cell for the purposes of photometry is, therefore, the rate of variation of the mean emission $\bar{\epsilon}$ with the temperature

of a completely radiating source when this is in the neighbourhood of $2,500^{\circ}\text{K.}$; if this is the same as the rate of

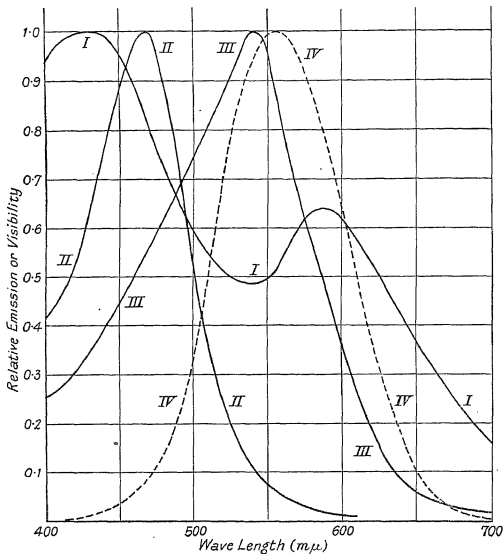


FIG. 10. VISIBILITY CURVE AND EMISSION CURVES FOR CERTAIN PHOTOELECTRIC CELLS

- | | |
|------------------------|--|
| I. Potassium on copper | ($1 = 4.9 \times 10^{-4}$ amperes per watt) |
| II. Rubidium | ($1 = 12.7 \times 10^{-4}$ " ") |
| III. Caesium | ($1 = 1.7 \times 10^{-4}$ " ") |
| IV. Visibility curve | ($1 = 621$ lumens per watt) |

variation of the luminous efficiency φ of the source, the cell is satisfactory. Relative, not absolute, rates of variation are required; we must compare $\frac{1}{\bar{\sigma}} \frac{d\bar{\sigma}}{dT}$ with $\frac{1}{\varphi} \frac{d\varphi}{dT}$, or (since

T is the same throughout) $\frac{d \log \bar{\sigma}}{d \log T}$ with $\frac{d \log \varphi}{d \log T}$. The following table makes such a comparison—

$\frac{d \log \varphi}{d \log T}$	.	.	.	.	.	5.47
$\frac{d \log \bar{\sigma}}{d \log T}$	{	Sodium	.	.	.	7.48
		Potassium	.	.	.	7.88
		Rubidium	.	.	.	7.27
		Caesium	.	.	.	5.69
		Potassium on copper	.	.	.	5.06
		Caesium on silver	.	.	.	5.68

It will be seen that caesium satisfies the criterion well; but its total emission is small. Caesium on silver oxide is certainly the best, if the facts concerning it are trustworthy, but it is possible to find potassium on copper cells which are quite satisfactory; for it must be remembered that all our values are averages, and that individual cells may depart appreciably from them. In any case, an exact agreement between the response of the cell and the visual effect of the lamp will, probably, have to be produced by the insertion of a slightly coloured filter before the cell. Since it is easier to find yellow filters which transmit the longer wavelengths without absorption than blue filters which transmit the shorter wavelengths without absorption, it is better to choose a cell for which $d \log \bar{\sigma}/d \log T$ is slightly greater than $d \log \varphi/d \log T$ than one for which it is slightly less. An alternative to the use of filters is the combination of the currents from different cells which diverge from agreement with the eye in opposite directions. There is then no loss of current by absorption of the light in the filter, but there may be some difficulty in securing that the light is always divided between the two cells in the same proportion (see pp. 166, 167).

CHAPTER V

THE ELECTRIC DISCHARGE

The Saturation Current.

If there is no gas present in the cell, and if a sufficient voltage is applied between the electrodes, all the electrons liberated by the light at the cathode will pass to the anode; the current flowing through the cell will be the primary photoelectric current studied in the two preceding chapters. But if a small voltage is applied, some of the electrons will return to the cathode and will fail to reach the anode; the proportion that reach it under any given voltage will depend on size of the cell and on the shape of the electrodes.

These facts are illustrated in Fig. 11, which shows the relation between the current i and voltage E in two vacuum cells, one of type A , Fig. 1 (which we shall henceforward term "spherical"), and one of type B (which we shall term "plane"). The primary photoelectric currents are supposed to be the same in the two cells, and accordingly the same current flows in both when any voltage above a certain limit is applied. This limiting current i_s , independent of further increase of voltage, is called the *saturation* current; it is equal to the primary photoelectric current. But at voltages less than that required to saturate both, the curves are markedly different; the curve rises less steeply in the cell in which a given voltage between the electrodes produces the smaller electric field at the surface of the cathode.

Current-voltage relations similar to those of Fig. 11 are characteristic also of thermionic valves and especially of diodes; there, too, we find a rise to a saturation current, independent of the voltage and determined by the electron emission from the cathode. But the circumstances that determine the rise are different. In the thermionic valve some of the electrons from the cathode fail to reach the anode at low voltages, because of the "space charge" established by their neighbours. The mutual repulsion of the

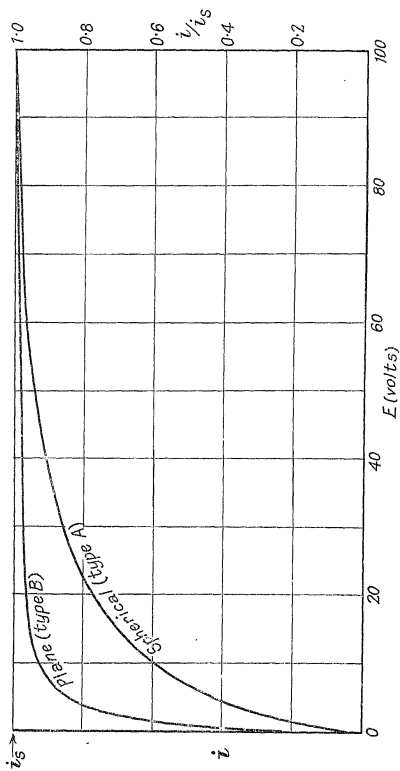


FIG. 11. CURRENT-VOLTAGE RELATION IN PLANE AND SPHERICAL VACUUM CELLS

electrons determines the rise; the voltage at which this becomes unimportant increases with the density of the electron stream, and the characteristic varies with the saturation current. In a photoelectric cell the density of the electron stream is usually too small for the effect of the space charge to be appreciable; the form of the characteristic is independent of the saturation current, so that if, in place of i , we plot the ratio i/i_s (as indicated on the right of Fig. 11), the same curve will represent the characteristic for all moderate illuminations. At very intense illuminations the effect of the space charge may appear, and the characteristic become somewhat flatter, but the change is seldom of practical importance.

The initial rise of the current with voltage in the photoelectric cell is mainly due to a cause that, in the thermionic valve, is almost concealed by the space charge. Some of the electrons leave the cathode with a finite velocity which represents the excess of the energy that they received from the light over that required for emergence; if their motion is originally directed towards another part of the cathode, force must be exerted on them to deflect them to the anode. The necessary force is obviously greater in a spherical than in a plane cell, and, consequently, the initial rise of the characteristic is less steep. If the cathode were perfectly smooth, a voltage of 10 or 20 volts would probably be enough for this purpose even in a spherical cell; more is actually required before the saturation current is reached, because the surface is rough and the electrons have to be dragged out of crevices. Further, we have seen that the original velocity of the electrons varies with the quality of the light; for this, and possible for other reasons, the initial part of the characteristic may vary with the quality. But we need not discuss the matter in detail because this part of the characteristic of a vacuum cell is unimportant practically; such cells are always used with voltages sufficient to give very nearly the saturation current. Perfect saturation is never attained, partly because the vacuum is not perfect, and partly because a sufficiently strong field enables some electrons to emerge from the cathode that would otherwise fail to do so. In Fig. 11 the current is still increasing even at the highest voltages. But this increase is of no practical

importance; for all practical purposes saturation is obtained when an increase of 10 volts does not increase the current by as much as 1 per cent (see page 78).

Ionization by Collision.

So much for the vacuum cell; the gasfilled cell requires much more careful consideration. The gas introduced has, of course, to be one that does not react chemically with the photoelectric material. Either argon or the mixture of neon and helium obtained by fractionating air is usually employed; the figures given below refer to argon, but qualitatively the facts are the same whatever gas is used.

The object of introducing gas is to magnify the primary photoelectric current through ionization by collision. We must start by expanding the brief description of this process given on page 2.*

The collision between a slowly moving electron and a molecule of a gas is similar to that between elastic or partially elastic bodies; the electron may give some of its kinetic energy to the molecule, but the colliding bodies separate essentially unchanged. If, however, the electron is moving fast enough, the molecule may be broken by the collision; an electron may be detached from it, leaving a remainder which is a positively charged ion. The energy required to detach an electron from a molecule, or to *ionize* it, is a definite property of the molecule called the *ionization potential* of the gas; it usually lies between 10 and 25 volts. An electron cannot ionize unless it possesses a kinetic energy greater than the ionization potential; if it has a greater energy, it will ionize if it makes a very direct impact, but not if the impact is glancing; if it ionizes the molecule, it loses energy equal to the ionization potential. An electron that initially possesses an energy equal to n times the ionization potential can thus ionize n molecules, if it makes a sufficient number of collisions of the right kind in passing through a gas. The ionization potential will be denoted by ϕ ; for, like the work function represented before by the same symbol, it is the voltage through which an electronic charge must

* The general theory of ionization by collision and of its bearing on the electric discharge is expounded by its author, J. S. Townsend, in his book, *Electricity in Gases* (Oxford Clarendon Press, 1915).

fall in order that it may acquire an amount of energy sufficient to liberate an electron.

When ionization has occurred, two electrons are present in the gas in place of one, namely, the original, primary electron, and the secondary electron ejected from the molecule. If the gas is placed in an electric field, both electrons will move to the anode, while the positive ion moves to the cathode. The anode receives a negative charge equal to twice that on an electron; the cathode receives an equal and opposite charge, represented by the charge on the primary electron that it loses and that on the positive ion that it gains. If each electron ionizes n times in passing through the gas, the current through it should be $(n + 1)$ times that carried by the primary electrons. Actually this is not quite true generally, because an electron may disappear again before it reaches the anode by encounter with a positive ion, produced by some other electron; it may *recombine* with this ion and form a neutral molecule again. But we shall leave recombination out of account through most of our discussion.

So far we have left out of consideration the source of the energy of the ionizing electron. If the quantum voltage of the radiation is sufficient, electrons liberated by the photoelectric effect may start from the cathode with an energy many times the ionization potential of the gas into which they emerge; if they make sufficient collisions, each may produce many ions; and, so long as the electric field is great enough to drag the ions and electrons to the electrodes, the primary current may be magnified many times. This state of affairs, in which the magnification is independent within wide limits of the voltage between anode and cathode, is found in the ionization chambers used for measuring X-rays, of which the quantum voltage is several thousand volts; such chambers are essentially gasfilled photoelectric cells. But the term is usually restricted to devices for detecting light in the visible and nearer ultra-violet region of the spectrum, where the quantum voltage is less than the ionization potential of any gas, and no primary electron can ionize on its own account. In such cells ionization by collision is induced by causing the primary electrons to pass through a strong electric field, and thus to acquire the requisite energy.

Factors Determining Magnification.

In order to investigate this process, something must be known about collisions that do not result in ionization. We shall assume that an electron loses all its energy when it collides and fails to ionize; the assumption is not correct, but it leads to nearly the right result. Accordingly, if the electrons are to acquire the energy necessary to ionize by travelling through the gas in an electric field, they must acquire it between successive collisions. If the electrodes are planes between which is a distance d and a difference of potential E , and if λ is the free path of the electrons between collisions, the energy acquired during the free path is $E\lambda/d$; in order that there may be ionization, $E\lambda/d$ must be greater than φ . If all free paths were equal the further investigation would be very simple; n , the number of collisions, would be given by

$$n = d/\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

n' , the number of ionizing collisions would be n or zero, according as $E\lambda/d >$ or $< \varphi$. At each ionizing collision the number of electrons travelling to the anode is doubled; consequently, if N_0 start from the cathode, N would arrive at the anode, where

$$N = N_0 \cdot 2^{n'} \quad (6)$$

N/N_0 is the *magnification* of the primary photoelectric current; it increases rapidly with n' .

Actually λ is not the same for all collisions, but varies fortuitously about a mean. This mean λ in any given gas is inversely proportional to the density, or if the temperature is constant, to the pressure p . Hence we may write

$$p\lambda = \lambda_\theta . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

When the variation of λ is taken into account, we have in place of (6)

$$N = N_0 \cdot e^{n'} \quad (8)$$

where $e = 2.713$. The proportion of collisions at which ionization occurs is still determined by the value of $E\lambda/d$, so that we may write

$$n'/n = f(E\lambda_o/pd) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

the function f increases with the argument $E\lambda_0/pd$.

n is still given by (5), so that

$$n' = \frac{pd}{\lambda_o} f(E\lambda_o/pd) \quad . \quad . \quad . \quad . \quad . \quad (10)$$

From (8) and (10) it appears that n' , and therefore N/N_o , the magnification of the primary current, increase with E if pd is constant. If E is constant, there is a value of pd for which n' is a maximum; this maximum increases with E . If pd is less than the value corresponding to the maximum, n' falls off because the total number of collisions is too small; if it is greater, n' falls off because the proportion of collisions resulting in ionization is too small. The value of pd for maximum n' is determined, as in the simple theory, by $E\lambda_o/\varphi$, and is actually of the same order of magnitude as that quantity. Thus for nitrogen at room temperature λ_o is about 0.045 (when p is in mm.), and φ is about 16 volts; consequently, if the plane electrodes are 1 cm. apart, and E is 200 volts, the optimum value of p should be about $200 \times 0.045/16$, or about $\frac{1}{2}$ mm.

(10) is still true if the electrodes are not parallel planes, so long as geometrical similarity is preserved when d is changed, though the function f will be different. Thus, with another f , (10) would be true if the electrodes were concentric spheres with a constant ratio between their diameters, and d were the diameter of either of them; for instance, it would still be true that variations of p and d do not change n' so long as pd is constant. But this would not necessarily be true if the diameter of one of the spheres were constant, while d , the diameter of the other, varied. Again, λ_o , and φ (which is involved in the function f) depend on the nature of the gas; (10) tells us nothing of how n' varies from one gas to another, unless the forms of f for the two gases are specified. Nevertheless, though the range of (10) is limited, it is useful in tracing the rather complicated variations of n' with all the possibly variable factors.

It is especially useful when only p and E vary. Fig. 12 shows some illustrations based on actual measurements for this case; the cell is spherical with a diameter of 6 cm. and a small central anode; the active metal is sensitized potassium, and the gas argon. N/N_o is plotted against E for various values of p ; the curves are the voltage characteristics

of the cell at different pressures of gas, for an illumination which would give a saturation current represented by 1. As the theory predicts, each curve rises continually with

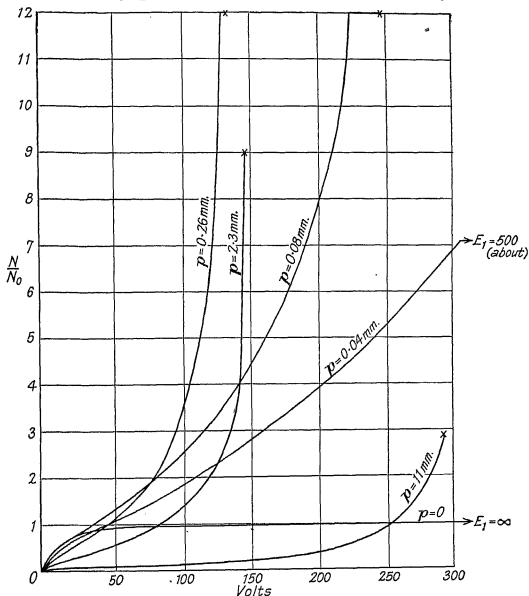


FIG. 12. RELATION BETWEEN MAGNIFICATION AND VOLTAGE AT VARIOUS GAS PRESSURES

E ; but the curves cross each other and, as E increases, the magnification at higher pressures increases relatively to that at lower pressures. Thus at $E = 100$ volts, $p = 0.08 \text{ mm.}$ gives higher magnification than $p = 2.3 \text{ mm.}$; but at $E = 140$ volts, $p = 2.3 \text{ mm.}$ is better.

It should be noted that, for small voltages N/N_0 is less than 1, and for none of the curves, except $p = 0$, is $N/N_0 = 1$ over any considerable range. The reason for this departure from the theory just expounded has already been explained; even in the absence of gas considerable fields are required to saturate the current and to drag all electrons to the anode; its presence hinders saturation further. At all the pressures shown, except $p = 0$, ionization by collision sets in before saturation is attained.

The Glow Discharge.

But there is another departure from the theory much more important practically, because it affects very greatly conclusions about the optimum pressure. According to (10) and (8) the magnification ought to increase indefinitely with E , and any magnifications, however large, ought to be attainable if sufficiently large potentials are available. Actually a limit is set to E by the influence of the positive ions, which have been left wholly out of account. They affect the current in two ways. First they cause the liberation of electrons from the cathode independently of the photoelectric emission; second, their presence in the neighbourhood of the cathode increases the electric field there, by reason of the charge that they carry. (The electrons similarly increase the field in the neighbourhood of the anode, but their influence is less important.) These two effects are closely related. It is still doubtful exactly how the positive ions liberate electrons at the cathode, whether by direct impact or by some indirect process; but it is certain that they do liberate them, and that the liberation is connected with the increased field due to the positive "space charge"; the greater the number of positive ions arriving at the cathode, the greater is the chance that each of them will liberate an electron additional to those liberated by the light. Accordingly, when once the action of the positive ions starts, it is cumulative and reinforces itself. As E is increased, and with it the number of positive ions, a stage is reached at which the current increases much more rapidly than it would according to (10), and, finally, a second stage in which the positive ions, produced by the collisions of the primary photoelectrically liberated electrons, in their turn produce

at the cathode secondary electrons as numerous as the primaries. When this second stage is reached, the current will continue to flow even when the light is turned off, for the liberation of the primaries is no longer necessary to its continuance; its magnitude will be determined not by the supply of electrons from the cathode, but by the disappearance of electrons and positive ions by recombination in the gas and at the walls of the vessel.

This condition is accompanied by a visible glow in the gas; it represents the *glow discharge*, which can be started in any gas at low pressure (such as that in a neon glow lamp) by the application of a sufficient field. When it occurs, the current through the cell no longer varies (or varies considerably) with the illumination; the cell is no longer a photoelectric cell. The highest potential that can be applied usefully to a photoelectric cell is the *glow potential*, E_1 , at which the glow starts and the current, increasing suddenly, becomes independent of the illumination; the useful part of the characteristic terminates at this point.

In Fig. 12 these terminations are marked by crosses (\times) when they lie within the limit of the diagram; when they do not, the voltage E_1 at which they occur is marked by a cross joined to the curve by an arrow. It will be seen that E_1 varies with the pressure; the manner of its variation is shown in Fig. 13, which refers to the same cell. In a cell of any other form, the curve would be very similar; it always has a flat minimum and a very rapid rise at lower pressures. The minimum value of E_1 depends both upon the nature of gas and of the cathode, but is very nearly independent of the arrangement of the electrodes.

The existence of the glow potential complicates greatly the choice of the optimum pressure for a given E , for which n' is a maximum. The choice indicated by (10) is valid only if at the pressure so indicated E is less than E_1 . Thus, in Fig. 12, if the curves continued indefinitely on the course indicated by (10), $p = 2.3$ would be preferable to $p = 0.08$ at all values of E above that at which the curves cross. Actually the characteristic for $p = 2.3$ terminates at its glow potential at $E = 145$; for higher values it does not exist for photoelectric purposes, and, therefore, $p = 0.08$ becomes preferable once more, and when E is 215 gives

magnification higher than any which can be obtained with $p = 2.3$.

Some other facts about the glow potential may be recorded

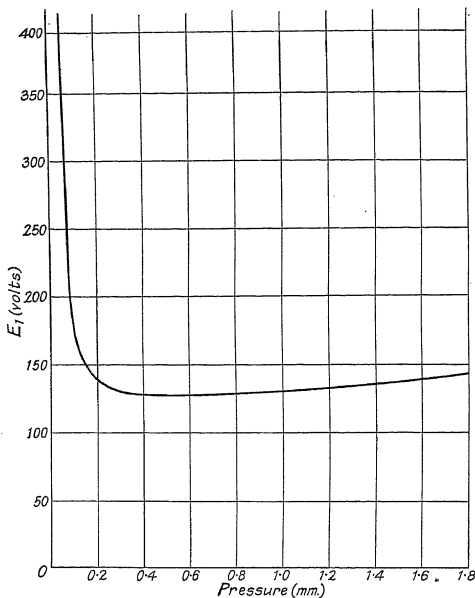


FIG. 13. VARIATION OF GLOW POTENTIAL WITH GAS PRESSURE

here for future reference. If the glow discharge is started by raising E above E_1 , and E is then reduced, ~~the glow discharge~~ does not stop when E_1 is reached again; the change is not completely reversible. In order to stop the glow, E has to be reduced to a considerably lower value E_2 , the

stopping potential. E_2 varies with the gas and the cathode and the pressure in much the same way as E_1 , having a minimum at about the same pressure. Again, E_1 and E_2 are not perfectly constant; E_1 is usually higher when the cell has stood for some time without a discharge passing than it is just after a discharge has passed; but even if an attempt is made to reproduce the condition of the cell by a series of discharges before measurements are made, appreciable variations will be found on different occasions. E_2 is less variable than E_1 , but is still not absolutely constant. These variations in E_1 , E_2 , and in the part of the characteristic immediately below E_1 are due to changes in the condition of the cathode, and are associated with variations in the photoelectric sensitivity, which were discussed in Chapter III (page 37); but they are not sufficient to affect the general truth of the statements made here.

The Corona and Arc Discharges.

The glow discharge is not the only form in which current can pass through the cell independently of the photoelectric current. If, when the cell is completely dark, the voltage across it is raised, no current exceeding 10^{-9} amp. will generally be found to flow through it until the glow potential is reached. But if a sensitive method of measuring current is employed, smaller currents will be detected at voltages considerably below E_1 ; they may rise to 10^{-9} amp., or even more, before the glow discharge sets in suddenly, with a current of several milliamperes. This *dark current*, as it is usually called, is troublesome when very small photoelectric currents have to be measured; for, unless the voltage is maintained considerably below E_1 , and magnification thereby sacrificed, it may be larger than the photoelectric current. On the other hand, it is of no consequence when the photoelectric current in the neighbourhood of E_1 is as great as 10^{-8} amp., as it is in most applications of cells. This second form of discharge, independent of the light, is known as the corona discharge, and has only been discovered and studied recently. Very little is known about its origin.*

* The processes involved in the starting and stopping of the glow discharge, in which the corona discharge is closely involved, have lately been investigated in great detail by J. Taylor and W. Clarkson. See W. Clarkson, *Phil. Mag.*, iv, 1002, 1341 (1927), where reference to earlier work is given.

At the other extreme, if the voltage is increased above the glow potential, and the current flowing through the cell is not limited by the exterior circuit, the glow discharge may turn into an arc, characterized by the heating of the electrodes to incandescence. To prevent the occurrence of an arc, which would destroy the cell immediately, a protective resistance of at least 10,000 ohms must always be placed in series with the cell; the current then cannot rise to the point at which the arc starts.

Change of the Characteristic with Illumination.

So far it has been assumed tacitly that the characteristic of the cell, and the magnification N/N_0 obtained at any pressure and potential, are independent of the illumination. This assumption is not true; the true facts are shown in Fig. 14, which refers to a plane cell and not to the spherical cell of Fig. 12. The general nature of the changes introduced by varying the illumination are the same in all types of cell; but they are easier to investigate completely in the plane cell.

In Fig. 14 the various curves are voltage characteristics similar to those of Fig. 12; but for convenience the ordinates represent the logarithms of the current i , not the current simply. Each curve refers to a different illumination, the relative value of which is marked against it. If the characteristic were independent of the illumination, the ratio of the currents for two values of E , or the difference in $\log i$, would be the same at all values of E ; the curves would be equi-distant through their course, and would differ only in being displaced parallel to the axis of $\log i$; they would all terminate at the same E_1 , that is to say, on the same vertical line. Actually, they are equi-distant only in the lower part of their course, most of which is omitted from the diagram because it is uninteresting; the characteristic is independent of the illumination only if E is greatly below the glow potential.

At the larger values of E , varying illumination produces changes of two kinds. The first, important at the lower illuminations, is a decrease of the glow potential with increasing illumination. The terminations of the curves lie on a regular curve (the thick line) which cuts off the curve

earlier the greater the illumination. Since the curves become steeper as they proceed, this means that the maximum magnification obtainable and the steepness of the curve just

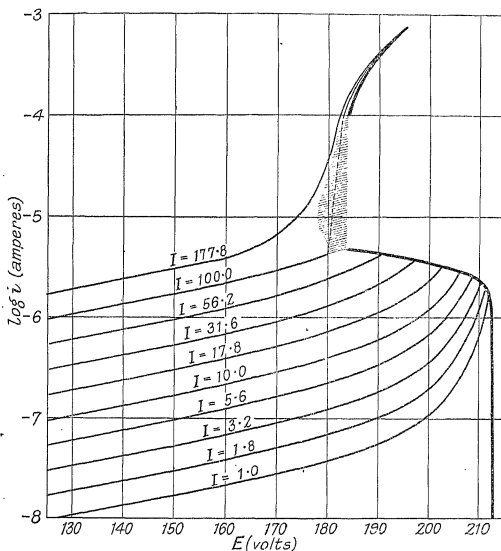


FIG. 14. VOLTAGE CHARACTERISTICS AT VARIOUS ILLUMINATIONS

before it terminates are less the greater the illumination. Although a greater current N is always obtainable from a greater emission N_0 , the maximum ratio N/N_0 decreases as the illumination increases. Our knowledge of the exact circumstances that determine the glow potential is not complete enough for a detailed explanation of these changes to be given. But the cause must doubtless be sought in the

action of the positive ions at the cathode. Since their effect is cumulative and not merely proportional to their number, the current must cease to be simply proportional to the illumination at potentials so high that their action is important.

The second change appears at the higher illuminations. The thick line, which represents how E_1 varies with the illumination, ends on the left; there is a least value of E_1 which cannot be surpassed however great the illumination. This minimum E_1 is actually E_2 , the *stopping potential*; E_2 is independent of the illumination; the termination of the thick line means that the glow cannot ever start at a potential less than that at which it would stop in the unilluminated cell. If the illumination is so great that, before E_2 is reached, the current flowing through the cell is already comparable with that carried by the glow discharge, then it is not to be expected that the attainment of potentials at which the glow would start at lower illuminations should produce the sudden increase of current characteristic of the starting of the glow. For such high illuminations there is no glow potential or stopping potential in the usual sense; there is gradual transition from the conditions of no glow to those of the glow; as the potential is increased, a stage is reached at which the current does not fall to zero, or even decrease appreciably, when the light is removed; the cell is now insensitive to light, and the passage to the glow discharge is complete. This stage is indicated in Fig. 14 by the point at which the characteristic merges into the upper thick line, which represents the relation between voltage and current in the glow discharge.

The two thick lines form together a "limiting curve" which divides the area of the diagram into two parts, that to the left, which represents combinations of voltage and current that can exist if the illumination is appropriate, and that to the right, which represents combinations that cannot exist at all. When a characteristic meets any point of the limiting curve, the cell changes from a state sensitive to light to a state insensitive; the lower part of the limiting curve represents unstable states and, when a characteristic meets this part, the cell immediately flies over to the upper part which represents the stable glow discharge. The

characteristics fall into two classes according as they terminate on the upper or lower part of the limiting curve, and there is a critical illumination which divides the two classes. Actually, the critical illumination cannot be determined precisely, because in this neighbourhood measurements are irregular; in the area shaded in the figure no consistent measurements at all can be made, but comparatively narrow limits between which it must lie can be found. There is no indication of any part of the limiting curve between the two portions shown.

The illumination affects the characteristic in two other ways of minor importance, which are not shown in Fig. 14. At very large illuminations the space charge due to the photoelectrically liberated electrons has the same effect as in the vacuum cell (page 54), but more markedly; the characteristic rises less steeply at very low voltages. Again, the frequency of the light is said to have some influence; but there is a difference between different observers concerning the magnitude and even the sign of the influence. Our own experiments disclose no effect of the frequency comparable with that of the intensity of the illumination; and since illuminations of the same intensity but different frequencies have seldom to be compared, any variations in the characteristic due to change in frequency will usually be masked completely by variations due to change in intensity.

Again an influence of the distribution of the light might be anticipated. If the light is concentrated on one small part of the surface and the rest is dark, it might be expected that this part alone would be effective, and that the shape of the characteristic would be that appropriate to high illuminations; while if the same light is spread uniformly over the whole surface, the form would be that appropriate to low illuminations. But this expectation is falsified; in cells of normal construction the form of the characteristic is determined almost entirely by the total light entering the cell, whether it is concentrated or diffused; if there is any effect of distribution, it is masked by changes due to the lack of uniformity of the sensitive surface (page 31). The reason is that the variations in the form of the characteristic are due to the actions of the positive ions. The positive ions do not return to the part of the cathode whence came the

electrons that produced them, but are distributed almost uniformly, even if the source of the electrons is concentrated in one spot. The distribution of the light does not determine the distribution of the positive ions or, therefore, the form of the characteristic. On the other hand, in very large cells with light distributed very unequally, some effect of the distribution may be appreciable.

CHAPTER VI

THE VOLTAGE-CURRENT CHARACTERISTIC

The Vacuum Cell.

WE must now re-arrange the facts set forth in the preceding chapter in a form more directly applicable to practice.

To the account of vacuum cells little need be added. The higher the voltage applied the better, for the more nearly will perfect saturation be attained; but a limit may sometimes be set by insulation leakage. In virtue of the second law of photoelectricity, the saturated current in a vacuum cell is accurately proportional to the quantity of light incident on the cathode, so long as the quality of the light is unchanged—a most important proviso. Departures from this law can sometimes be detected; they are due either to incomplete saturation, or to incomplete definition of the area of the cathode for the reason mentioned on page 5, or to incomplete fulfilment of the proviso.

Gas-filled Cell. General Considerations.

But in the use of the gas-filled cell the choice of voltage is a matter of great moment.

The considerations that have to be taken into account are best discussed with the aid of Figs. 15 and 16, which express the facts of Fig. 14 in a different way. They refer again to a particular plane cell (type *B*) filled with argon and having a potassium cathode.

In Fig. 15 the current through the cell is plotted against the illumination. The various continuous curves refer to various voltages applied to the cell, which are marked against them; the curves end on the dotted curve when the applied voltage becomes equal to the glow potential, and the current ceases to be controlled by the light. The dotted curve is a reproduction in another form of the lower part of the limiting curve of Fig. 14. The upper part of the limiting curve lies beyond the margin of the diagram; the curves for 182 and 170 volts do not terminate at all.

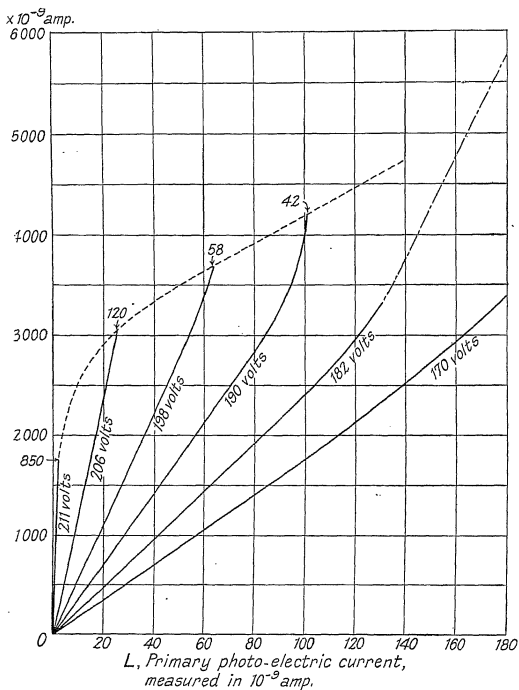


FIG. 15. VARIATION OF CURRENT WITH ILLUMINATION AT
VARIOUS VOLTAGES

The illumination represented by the abscissae is here measured by the saturated current which it would excite in the same cell if it were evacuated. All questions of the quality of the light and of the photoelectric properties of the cathode are thus avoided; they are irrelevant to our present inquiry. For the voltage characteristic depends on the electronic emission from the cathode, and not on the means by which it is excited. But since it is desirable to have in mind some idea of the illuminations involved, it may be recorded that an illumination represented by 1 is due to the incidence of about 0.001 lumen from a gas-filled lamp on a potassium cathode. In virtue of this method of estimating the illumination, the diagram shows directly the magnification of the primary current produced by the gas; it is the ratio of the ordinate of any point to its abscissa. The magnifications at the terminal points of the various curves are marked along the dotted curve.

The curves illustrate again some facts already noted. If it is necessary that the current should be proportional to the light, only the straight part of the curves of Fig. 14 must be used; either feeble lights must be used or, with stronger lights, low voltages. The limit at which marked deviation from proportionality occurs is fixed by the current rather than by the light; for all lights it lies between 2 and 3 microamps. Again, if proportionality is not demanded, and the object is to obtain the greatest current from a given light, the maximum current, limited by the glow potential, does not increase nearly so rapidly as the light; over most of the range of Fig. 15 the maximum magnification attainable increases as the light decreases, and the maximum current is more nearly independent of the light than proportional to it.

But this is not true at either of the limits of that range. It is not true when the light is very small on account of the dark current (page 63). The dotted limiting curve does not really fall to zero with the light as shown; the current just before the glow potential is finite even when the cell is completely dark. The incidence of a small light increases this current by an amount which represents an enormous magnification of the primary photoelectric current, but as it is not large compared with the current that flows in the

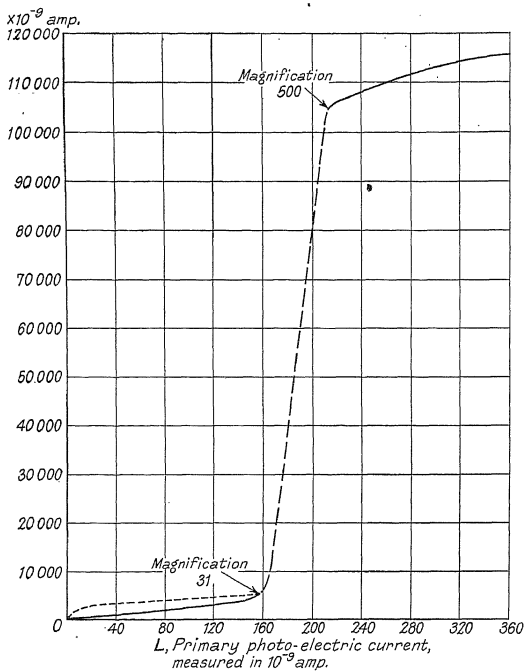


FIG. 16. RELATION BETWEEN CURRENT AND ILLUMINATION AT
VOLTAGE E_2

dark, it cannot be measured with great accuracy. The dark current falls more rapidly with the voltage than the photoelectric current, and can be made negligible by reducing the voltage well below the glow potential. Such reduction is necessary if accurate measurements are to be made; it involves a sacrifice of magnification; the practical magnification with very small lights may actually be less than that with somewhat larger lights which give photoelectric currents sufficiently large to mask the dark current.

At the other extreme (see Fig. 16) the magnification increases greatly as the light increases past the critical value which (in Fig. 14) marks the change from a characteristic that cuts the lower part of the limiting curve to one that meets the upper part; but once this limit is past, the magnification falls again and the maximum current becomes almost independent of the light. The change occurs, as explained before, when the glow potential E_1 falls to its minimum, which is the stopping potential E_2 . For lights greater than the critical, little is gained by using any voltage greater than E_2 ; the relation between light and current is therefore given fully by the right-hand portion of Fig. 16, in which the voltage is always E_2 . For lights less than the critical, the currents obtained with E_2 are, of course, less than those obtained with higher voltages; the dotted curve, which is a reproduction of that of Fig. 15, shows the greatest currents obtained with these small lights. The enormous increase in maximum current when the critical illumination is reached becomes fully evident.

Different Types of Cell.

Figs. 15 and 16 refer to one particular cell. The statements based on them are true qualitatively of all gas-filled cells; but in other cells great quantitative differences may be found, and to represent them, the diagrams, though retaining their general form, may have to be greatly distorted.

In a given cell, the characteristic changes with the nature and pressure of the gas-filling and, in a lesser degree, with the material of the cathode; for the glow potential E_1 and the stopping potential E_2 are determined by these factors. But, within the limits imposed by other considerations,

changes due to this alteration can be represented approximately by a change in the voltage scale of the diagram, or, more generally, by a stretching of the diagram, not necessarily uniform, parallel to the horizontal axis. This statement does not pretend to complete accuracy, and some further remarks on this matter will be found in Chapter VIII; but it is probably a sufficient guide for most practical purposes, and the only guide that can be offered here. Since no simple and general laws are known relating the parameters of the characteristic to the nature of the cathode and of the gas-filling, the matter could not be discussed fully without presenting an enormous and indigestible mass of facts.

Much greater and more important changes of the characteristic accompany changes in the type of cell, that is to say, in the dimensions and geometrical form of the electrodes and containing vessel. Here, again, it is quite impossible to discuss all possible types, or even all types that are in common use. It will be necessary, and is probably sufficient, to consider extreme types. One extreme is the plane cell to which Figs. 15 and 16 refer; the opposite extreme is the large spherical cell (type *A*). In this type the variation of the glow potential with the illumination and the difference between the maximum and minimum glow potentials are much greater, and so is the critical illumination at which the change from the upper to the lower limiting curve occurs.

These differences are shown in Fig. 17, which is similar to Fig. 14. The full-line curves of Fig. 17 are transferred from Fig. 14, and refer to the same plane cell; the dotted curves are those of a spherical cell having the same emission, and therefore the same primary current, and the same maximum glow potential.

The characteristics of the spherical cell are steeper, especially at low voltages and near the glow potential. With a flux less than 0.1 lumen, the maximum current it gives is rather greater than that of the plane cell. But between 0.1 and 1 lumen, a very important range, it is much less, because the characteristic of the plane cell has passed to the upper limiting curve while that of the spherical cell remains on the lower limiting curve. But at 10 lumens—a flux very seldom used

—the spherical cell has the higher maximum current, because the current carried by the glow discharge is much greater.

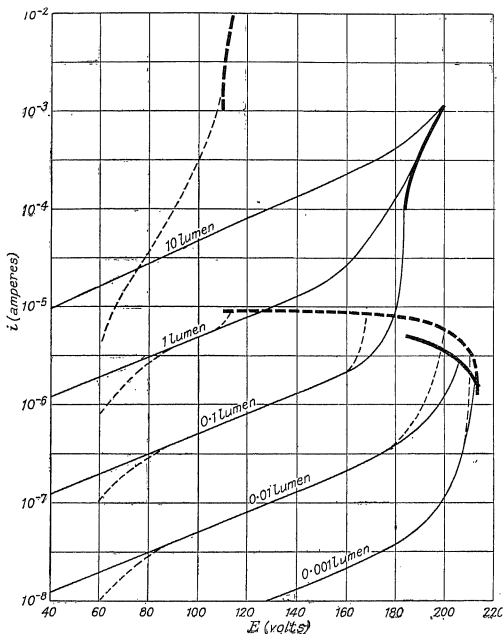


FIG. 17. VOLTAGE CHARACTERISTICS OF SPHERICAL AND PLANE CELLS
(Continuous lines refer to plane cell; dotted lines refer to spherical cell)

There is a further difference of some importance not shown by the figure. The dark current, carried by the corona discharge, is much smaller in the spherical cell; and, therefore,

with very small fluxes ($\cdot 0001$ lumen or less) higher magnifications can be used without the photoelectric current being masked by the dark current.

The Adjustment of Voltage.

We will now proceed to state concisely the rules for adjusting the voltage of a gasfilled cell based on these facts. They apply equally to all types of cell, except, possibly, those with thin film cathodes (see page 34).

First, in order to protect the cell from the damage which it would suffer if the glow discharge turned into an arc, a protective resistance of at least 10,000 ohms must be placed in series with the cell.

If it is desired to obtain the greatest possible current from a given light, the greatest light to which the cell is to be subjected in use must be thrown on the cell, and the voltage across it raised till the glow discharge starts. The voltage is lowered immediately (for it is not advisable to allow the glow discharge to pass for too long a period) till the discharge stops. This process is repeated two or three times until the stopping potential is constant. The voltage is now raised to a value slightly below the last value of the glow potential. Ten volts below is often recommended, but with a good cell 5 volts is sufficient, and even 2 volts can be used if the voltage is really constant.

If there is no limit to the light which may be thrown on the cell, or if it is essential that its action should never be interrupted by the occurrence of the glow, the voltage should be just below (say 2 volts below) the stopping potential. This may be determined without throwing light on the cell, for it is almost independent of the illumination.

If it is necessary that the relation between current and light shall be linear, a lower voltage again may have to be selected; it can only be determined by trial. A useful method of determining whether the relation is linear is given on page 194.

If very small lights are used and the dark current is important, the voltage must be raised until the dark current becomes comparable with the photoelectric current.

Most cells with potassium cathodes (and to a lesser extent in those with other cathodes) the passage of the glow

discharge increases the emission very notably (see page 40); it may rise to three times the value given in Chapter IV. There are potassium cells in which the emission falls when the discharge passes; but these are thoroughly bad cells and should not be tolerated. Accordingly, when the voltage is adjusted by the rule which involves passing the discharge, the cathode will start at its maximum emission. If now a large current is passed through the cell, i.e. one not much less than that which flows in the glow discharge, the emission will remain high; but if only a small current is passed, it will fall and regain its "rested" value after some hours. If, therefore, small currents are to be used and constancy is important, care must be taken not to pass the discharge or, alternatively, to pass it frequently for a few seconds so that the maximum emission is always restored. Another plan is to use some cathode which is comparatively insensitive to the discharge, such as unsensitized potassium; but this plan involves a considerable sacrifice of emission. However, real constancy in a gasfilled cell cannot be obtained in conjunction with high magnifications, except by exposing the cell for long periods to a constant light at constant voltage.

The Characteristic Conductivity.

So far we have assumed that the voltage across the cell, when once adjusted, remains independent of the current passing through it. This assumption is never accurately true. For there is always some resistance in the circuit exterior to the cell; if a constant voltage is applied to the circuit as a whole, that applied to the cell will fall as the voltage drop in the exterior resistance increases with the current. If the exterior resistance is merely that required to protect the cell from damage, i.e. about 10,000 ohms, the variation of the voltage across the cell with the current will be generally inappreciable; but in certain methods of using cells much larger resistances than this are employed, and their effect is very important.

If the illumination of the cell is constant and the voltage across it is varied, a small change in voltage dE will produce a proportional small change in current di . Accordingly, for small changes of voltage the cell behaves as if it were an

ohmic conductor with resistance $r = \frac{dE}{di}$, and conductivity $\Gamma = \frac{di}{dE}$. When the illumination varies, but the voltage about which the small changes occur is constant, Γ is proportional to i ; hence if we write

$$\gamma = \Gamma/i = \frac{1}{i} \cdot \frac{di}{dE}$$

γ (which is called the characteristic conductivity) is nearly independent of the illumination, and a function only of the voltage; it is the relative increase in magnification due to an increase of 1 volt in the voltage, so that if the current through the cell increases by x per cent when the voltage is increased by 1 volt, then $\gamma = x/100$.

Because of the characteristic conductivity, the current is not proportional to the illumination when there is much exterior resistance, even if the cell works on a part of the characteristic where there would be proportionality if the applied voltage were constant. Let i_0 be the illumination, measured by the primary photoelectric current, m the magnification at the voltage E , R the exterior resistance. Then i , the current in the circuit, is given by

$$i = i_0 m (1 - \gamma R i)$$

If we are measuring the current by the voltage drop e in the exterior resistance, then the appropriate formula is

$$e = i_0 m R (1 - \gamma e)$$

In each case the expression in brackets is a correcting factor determined by the characteristic conductivity of the cell. Some idea of its magnitude should be given. If the cell is working on a part of its characteristic far from the glow potential, γ will be of the order of 0.02; if it is working near the glow potential it may be as high as 0.1. Accordingly, if an error of 1 per cent is important, the drop across the exterior resistance must not exceed 0.5 volt in the first case, or 0.1 volt in the second. If the exterior resistance is only 10,000 ohms, the error will not enter until the current is $10\mu A$. In a vacuum cell γ need not be greater than 0.001, and the effect of the characteristic conductivity is always negligible.

CHAPTER VII

INTERMITTENT CURRENTS

Use of a Current-limiter.

So far we have supposed that illumination is to be detected or measured by changes of the current through the cell. The voltage across the cell has been regarded as fixed during any given experiment (apart possibly from a small drop in the exterior resistance), and we have asked how the current will vary with this fixed voltage and with the illumination. But for some purposes an inversion of this method is convenient; the current through the cell is fixed, and illumination is detected or measured by changes in the voltage; we have then to ask how the voltage will vary with the fixed current and with the illumination.

A constant but adjustable current can be maintained in any circuit if it includes a *current-limiter*, that is to say, a device which will not pass more than a certain current, however great the E.M.F. applied to the circuit. The most convenient form of current-limiter is an electronic valve, which possesses a saturation current. A vacuum photoelectric cell might be used for this purpose, the saturation current being controlled and varied by the illumination of the cathode; but it is generally more convenient to use a thermionic diode, in which the temperature of the cathode is controlled by the current heating it. (Any triode can be converted into a diode by simply joining grid and anode together.) So long as the voltage between the electrodes of the diode is sufficiently high and the emission from the cathode sufficiently small, a current will flow through the diode determined entirely by that emission and controllable by the filament circuit. In place of a current-limiter of this kind, setting a definite upper limit to the current that can flow through the circuit, an ohmic resistance might be used with much the same result, if its resistance were so high that the voltage drop across it was always large compared with that across the cell; but the principles involved are clearer if the

saturated current-limiter is used, and in practice it is more convenient.

Intermittent and Continuous Currents.

Suppose then that a thermionic current-limiter is placed in series with a gasfilled photoelectric cell, as shown in Fig. 18, that a large potential E_o is applied to the circuit,

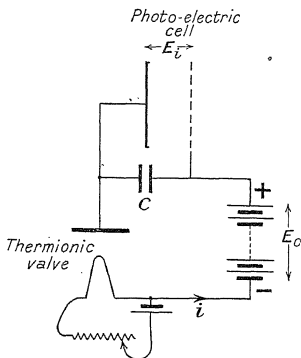


FIG. 18. USE OF A CURRENT LIMITER

and that the filament current of the limiter is adjusted so that the saturated current is i . Then, if there is a point with an ordinate i on the voltage characteristic of the cell for the particular illumination to which it is subjected, a steady current i will flow through the cell; the voltage across it will take up the value E_i , corresponding to i , on the characteristic; and the balance of the voltage, $E_o - E_i$, will be taken up by the current-limiter. (We see now what is meant by a "large" potential E_o ; it must be such that $E_o - E_i$ is always sufficient to saturate the current-limiter.) But there may be no point with an ordinate i on the characteristic of the cell; for the greatest value of i on the characteristic is that corresponding to E_1 , the glow potential;

this we shall call i_1 . i_1 increases with the illumination, and can always be made less than i by decreasing the illumination. What will happen when $i > i_1$, and there is no voltage which can send steadily through the cell the current that the limiter permits to pass?

The answer is that an intermittent current will flow, of which the mean value is i . There is always a capacity C (Fig. 18) in parallel with the cell, even if no condenser is added; for the electrodes of the cell form a condenser. When the current i is switched on, C will begin to charge up, and will continue to charge up till the voltage across the cell reaches E_1 . Then a glow discharge will pass through the cell carrying a current i_1' which is very much greater than i_1 . If (as we shall suppose at present) i lies between i_1 and i_1' , C now begins to discharge, because the current i_1' flowing out of it through the cell is greater than the current i flowing into it from the current-limiter. The current will continue until the voltage across the cell falls to the stopping potential E_2 , and the current to some value i_2' corresponding to this potential in the glow discharge. If (as we shall assume) i_2' , as well as i_1' , is greater than i , the glow discharge must now cease, for the current passed by the limiter cannot maintain it; when it ceases, the current falls to i_2 , the value corresponding to E_2 on the voltage characteristic of the cell; since i_2 is less than i_1 and, therefore, less than i , C begins to charge up once more and the cycle is repeated.

The process may be illustrated by extending the voltage characteristic of the cell. Hitherto this has been confined to potentials less than E_1 , so that the current is controlled by the illumination. But there is also a definite relation between current and voltage when the potential exceeds E_1 and the glow discharge is passing; this relation, which is represented by the upper part of the limiting curve in Fig. 14, is another part of the characteristic. These two parts are usually distinguished as the Townsend and the glow characteristics; Fig. 19, which is a reproduction of part of Fig. 14, shows the glow characteristic and the Townsend characteristics for a large and a small illumination in a plane cell. The current i determined by the current-limiter may be represented by a straight line XX . If this cuts either the Townsend characteristic or the glow characteristic a constant

current flows through the cell; but if it lies between them, as shown, a constant current cannot flow; the cycle just

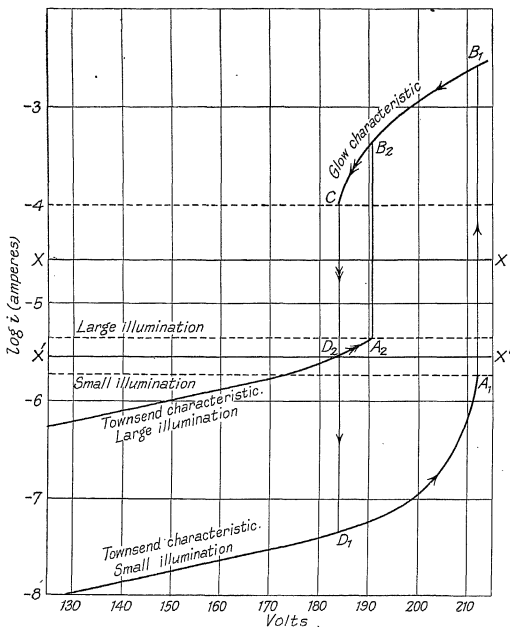


FIG. 19. CONDITIONS FOR INTERMITTENT CURRENT

described will occur; the point representative of the state of the cell will pass up the Townsend characteristic to A_1 or A_2 (according to the illumination), jump across to B_1 or B_2 , travel down the glow characteristic to C , and jump back

to the Townsend characteristic at D_1 or D_2 . The condition that the current shall be continuous is that XX lies above the upper or below the lower dotted line, this latter varying with the illumination; the condition that the current shall be intermittent is that it lies between them.

The Critical Illumination.

Intermittent discharges of this kind can be made to occur in any discharge tube by placing a condenser across its terminals and limiting the current in the exterior circuit. They have been closely studied in neon lamps, and put to a variety of practical uses. The difference between the "flashing" neon lamp and the gasfilled photoelectric cell in this matter is that the cell possesses a definite Townsend characteristic, variable with the illumination. As the illumination increases, the whole characteristic rises and the distance between the horizontal lines diminishes. If then the current-limiter is set so that XX lies between these lines at a small, but not at a large, illumination (e.g. so that it lies at $X'X'$), increase of the illumination on the cell will make the lower line rise above XX , which will then cut the Townsend characteristic. This means that i can be set so that the current through the cell is intermittent if the illumination is small, but becomes continuous if the illumination is sufficiently great. The change from an intermittent to a continuous current can easily be detected, e.g. by means of a telephone placed in the circuit; the intermittent current will give rise to a series of clicks, but when the current becomes continuous, there will be silence. Here, then, is another way of using a photoelectric cell to detect light, which has some very important uses.

In these uses it is important to know the relation between L , the illumination of the cell, and the critical value of i at which the change between a continuous and an intermittent current occurs. According to the simple theory of the matter that has just been expounded, this value is i_1 , the current at the glow potential \bar{E}_1 . But the relation between this i_1 and L is given by the dotted curve in Fig. 15; if the simple theory were true, the same curve ought to represent the relation we seek between L and the critical value of i . This curve is reproduced dotted in Fig. 20, which shows also the relation

determined experimentally for the same cell. The two curves are very different. In the experimental curve there are no values of i at all corresponding to illuminations below one limit or above another limit, while between these limits there are in general two values of i corresponding to the same L . Let us examine the meaning and cause of these discrepancies,

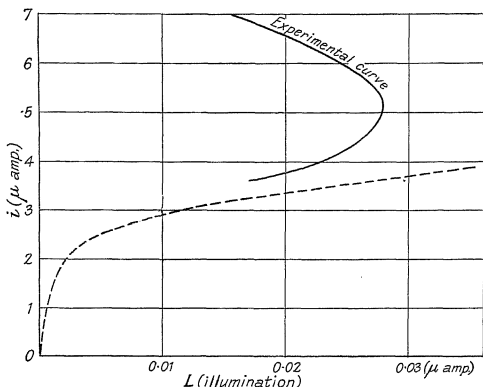


FIG. 20. RELATION BETWEEN CURRENT AND CRITICAL ILLUMINATION IN A PLANE CELL

and inquire what elements have to be added to the theory to explain them.

For this purpose it will be convenient to invert the relation in our minds and consider the critical illumination L that is required to make a given current i change from intermittent to continuous, rather than the critical current at which the change occurs for a given illumination; that is to say, according to the ordinary convention, Fig. 20 must be turned through a right angle, so that i is the abscissa and L the ordinate. We start then with small values of i . Here there is no critical illumination, for, even when the cell is dark and, according to Fig. 15, $i_1 = 0$, the current through

the cell is continuous and not intermittent. The reason for this discrepancy lies in our neglect of the corona discharge, which gives rise to the dark current. If the conditions are those supposed to prevail in Fig. 15, and the resistance in the exterior circuit is small, this current is so small as to be inappreciable on the scale of that diagram. But the greatest current that the corona discharge can carry increases with the exterior resistance—the theory of the matter is so obscure that no reason for this increase can be given—and when the very large resistance represented by the current-limiter is present, it rises to much higher values. The current is continuous even when there is no light; there is no critical illumination, and the curve of Fig. 20 does not start until i exceeds i_c , the greatest current that the corona discharge can carry.

A further complication, not shown in Fig. 20, enters for the same reason; i_c depends on the capacity in parallel with the cell, decreasing as the capacity increases up to a certain limit. Accordingly, the point at which the curve of Fig. 20 starts and its initial course are influenced by the capacity C . The value of C in Fig. 20 is supposed to be the least that reduces i_c to its minimum; this is about $100 \mu\mu F$; if C were reduced, the curve would not start until a still higher value of i was reached.

When light is thrown on the cell, the photoelectric current is added to that carried by the corona discharge. Possibly there is some interaction, so that the total current is not exactly the sum of those which would flow in the absence of one or the other; but this possibility may be neglected. Accordingly, once the curve starts, it follows roughly the course of the curve of Fig. 15; L rises with i , but the value of i corresponding to any L is greater than in Fig. 15 because i includes a larger corona discharge.

If, however, i is increased still further, an entirely new departure from the simple theory appears. A maximum of the critical illumination is reached, and thereafter L decreases as i increases. This is because i_2' , the current at which the glow discharge stops is not, as we have assumed, independent of L ; as L is increased, i_2' decreases, though the decrease is not easily detected except when the current in the exterior circuit is limited. Increase of L in Fig. 19

not merely raises the lower dotted line, it also lowers the upper dotted line; the current may become continuous, not because the lower line rises above XX , but because the

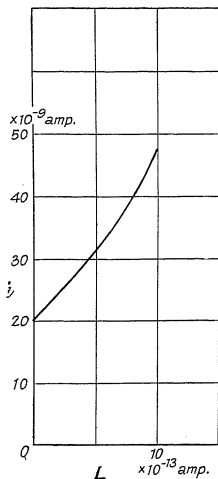


FIG. 21. RELATION BETWEEN CURRENT AND CRITICAL ILLUMINATION IN SPHERICAL CELL

upper line falls below it. The maximum critical illumination occurs at the value of i , such that XX is at the level where the lower and upper lines meet as the illumination is increased. For small values of i the critical illumination is that at which the lower line reaches XX ; this illumination increases as XX is raised. For large values of i , it is that at which the upper line reaches XX ; this illumination decreases as XX is raised. The curve of Fig. 20 finally terminates, as explained before, when i is so great that XX reaches the upper line of Fig. 19 even when there is no illumination, so that the glow discharge can pass even when the cell is dark.

Figs. 19 and 20 refer to a plane cell. If we substitute a spherical cell, the general nature of the relations is really unaltered; but once more there is a change of degree which appears experimentally as a change of kind. In the first

place i_c is very much smaller, and the curve of Fig. 20 therefore extends to very much smaller currents and critical illuminations. Fig. 21 gives the corresponding curve for a spherical cell, the part shown being that for currents so small that the corresponding part does not exist at all in a plane cell; we shall see later that this is the part important experimentally. (Here, again, L is measured by the saturated current which the illumination would give if the cell were

evacuated.) However, there is still a small corona discharge and a minimum i_c below which the curve does not exist at all, but it is so small that it is not visible at all on the scale of Fig. 21; moreover, this value, and the form of the early part of the curve, varies with the capacity C in the manner already explained.

In the second place, there is no definite maximum critical illumination. If it existed, it would be expected at a much higher value than in the plane cell, because the upper dotted line of Fig. 15 lies at much higher currents. Actually, the critical illumination increases continually with i until values much greater than those of Fig. 20 are attained, and the curve finally terminates before the upper dotted line is reached, because the changes become irregular and irreversible; the current can be changed from intermittent to continuous by increasing the light sufficiently, but it does not become intermittent again when the light is turned off. The same thing happens to a minor degree in the plane cell on the upper branch of the curve of Fig. 20. But these matters are of no consequence for the purpose, because the illuminations at which they occur are beyond the practical range; for all important illuminations L increases regularly with i in the spherical cell.

The Period of Intermittence.

So far we have only distinguished intermittent from continuous current, and have said nothing of the frequency of intermittence or the period of the cycle. This period is made up of two parts. During the first, C is charged up from E_2 to E_1 by the difference between the current i , and the current i' , varying with E , which leaks through the cell. Consequently

$$C \cdot \frac{dE}{dt} = i - i' \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

so that, if we write $i' = f(E)$, the period τ_1 , occupied by this part of the cycle, is given by

$$\tau_1 = C \int_{E_2}^{E_1} \frac{dE}{i - f(E)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

In the second part of the cycle, the condenser C discharges; if the current flowing through the cell is now $i_1' = f_1(E)$, the period is similarly

$$\tau_2 = C \int_{E_1}^{E_2} \frac{dE}{f_1(E) - i} \quad (13)$$

The complete period is $\tau = \tau_1 + \tau_2$, but $f_1(E)$ is always much greater than $f(E)$, and, though $f(E)$ is less than i , $f_1(E)$ is much greater when i is small. Then τ_2 will be very small compared with τ_1 , and we may identify τ with τ_1 .

If the simple theory of page 81 were true, $f(E)$ would be zero when the cell is dark, and we should have

$$\tau = \frac{C(E_1 - E_2)}{i} \quad (14)$$

Actually this is not true, because $f(E)$ rises to i_c even when the cell is dark. This does not affect the conclusion that τ increases with C and decreases with i ; but τ calculated from (14) will be less than the actual value. The effect of illumination is to increase $f(E)$, but to decrease E_1 ; these effects work in opposite directions, but actually, for small currents and illuminations, the second is the greater and τ is increased by illumination, becoming infinite when the critical illumination is attained and the intermittence ceases. Fig. 22 shows the relation between τ and L in the spherical cell to which Fig. 21 refers for two values of i ; it should be observed that τ varies much more rapidly with L when i is small. The capacity C was here $100\mu\mu F$; the value of τ indicated by (14) is marked by a cross on the axis of τ .

In the plane cell the corresponding curve would not start at all until L attained much larger values, and the greatest value of τ would be much less. But the relations for the plane cell are more interesting when i is large, corresponding to a point on the upper branch of the curve of Fig. 20. Here the first of the two effects of the light becomes more important; increasing illumination reduces so greatly the difference of potential ($E_1 - E_2$) through which C is charged and discharged that it decreases the whole period τ ; light makes the frequency of intermittence greater, and, when the critical illumination is reached, the intermittence vanishes because its frequency has become infinite and its period zero. The

process is too complicated to be treated theoretically, but the facts are perfectly plain; when i is small, the period of intermittence increases, and the frequency decreases, with

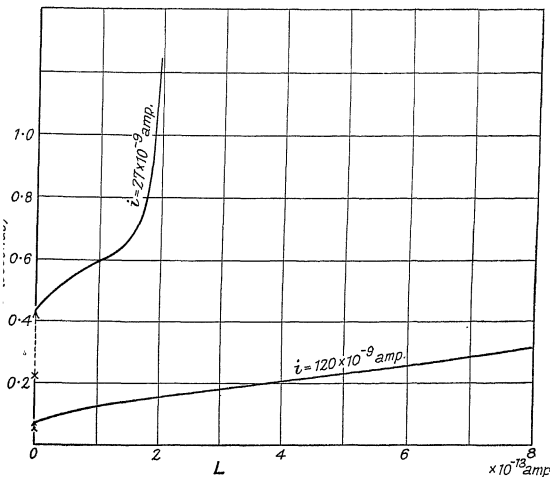


FIG. 22. VARIATION WITH ILLUMINATION OF PERIOD OF INTERMITTENT DISCHARGE IN SPHERICAL CELL

illumination; when it is large, the period decreases and the frequency increases. Between these two ranges there is one in which the period is almost independent of the illumination, and when the critical illumination is reached, the intermittence ceases without any marked change in frequency. There are the same three ranges in the spherical cell; but for the reason already explained only the first is important.

CHAPTER VIII

THE CHOICE OF A PHOTOELECTRIC CELL

Vacuum and Gasfilled Cells.

THE main considerations that should determine the choice of a cell for any particular purpose are set forth in the preceding chapters; a few minor considerations will be discussed more appropriately later, together with the uses to which they are relevant. But a summary of the conclusions to which they lead may be useful.

The great majority of cells offered for sale are gasfilled cells, and for many important uses no others are worth consideration, but it cannot be insisted too strongly that vacuum cells have every advantage over gasfilled cells except that of sensitivity. If it is possible, by increasing the amount of incident light, to obtain the current that is desired from a vacuum cell, or if, by improving the means of utilizing current, the output from a vacuum cell can be made adequate for the work in hand, then no thought of gasfilled cells should be entertained. Vacuum cells are instruments of precision and beautifully simple to handle; gasfilled cells need skilled handling, and are never wholly trustworthy.

Vacuum Cells.

The emission, determined by the cathode material, is the main consideration; here the data of Chapter IV are decisive. For most work in the visual spectrum, the potassium cell or one of the thin film cells are the best.

But there are some secondary considerations. Thin film cathodes are certainly more constant in their emission over long periods than thick layers, and are therefore preferable for highly accurate work. The slow and irregular variations of thick layers in vacuum cells are probably due largely to temperature changes which cause distillation of the surface layers from one part to another; though temperature has little direct effect on emission, it has an indirect effect and changes of temperature are therefore to be avoided.

In choosing the form of the cell the advantage of a cathode that does not form part of the wall is very material (page 5), and need not be counterbalanced by any disadvantage. A field as uniform as possible between the electrodes leads to lower saturation voltages. The spherical type is undesirable for both these reasons, and does not seem to gain anything material from the application of the black-body principle (cf. page 8); moreover, that principle can be employed by placing a reflecting enclosure outside the cell rather than inside.

Since the currents are small, insulation is very important in vacuum cells. Internal guard rings are desirable, but not absolutely necessary in potassium or sodium cells. Caesium and, to a less extent, rubidium are very apt to form conducting films on the glass; cells filled with these metals should always have guard rings, which, however, do not prevent leakage between the "insulated" electrode and earth. Caesium in thick layers has no advantages as a cathode except for very special purposes; if it had, this defect would be important. In cells with thin films of caesium as cathode this defect is less prominent; for the excess of the metal, which would form films on the glass, is removed. External insulation is, of course, equally important; external guard rings can be provided by wrapping wire round the cell between the two electrodes; the inclusion of both electrodes in a single "cap" is not desirable, though high insulation can be maintained by suitable methods of capping.

Gasfilled Cells.

In a gasfilled cell, the sensitivity is determined by the "effective emission," which is the product of the emission and the magnification. We must first notice that these two factors are not completely independent, as might be concluded from our previous discussion.

With electrodes of given form immersed in a given gas at a given pressure, the magnification at all lower voltages is the same whatever the cathode material; but the glow potential depends on that material; the maximum magnification will be greater the greater the glow potential. Sensitized potassium gives a rather higher glow potential than

unsensitized potassium, and both a higher glow potential than caesium. Among these three materials the maximum magnification increases with the emission for white light, and the differences in effective emission are even greater than those shown in the table on page 44. But the rule is not general; sodium has a rather higher glow potential than potassium, and so have the metals suitable for use in the ultra-violet.

Again it must be remembered that the glow discharge in a gasfilled cell may alter the emission; in some cells it increases it (page 40); this effect seems greater with sensitized potassium than with any other cathode. On the other hand, thin film cathodes are usually, if not always, damaged by the glow discharge or, indeed, any large current through the usual filling gases (helium, neon, argon); if they are used with such gases, magnifications must be kept low in order to avoid damage. The potassium on copper cathode can be used with a filling of hydrogen, the discharge through which is harmless; but this is inconvenient, since the hydrogen is continually absorbed, and the filling has to be renewed constantly through a palladium tube.

The results of these interactions between the two factors determining effective emission is to improve the position of the sensitized potassium cathode as against all others. If white light is to be used, it is preferable to all others in gas-filled cells; but, as was pointed out before, new developments may change the position. In the ultra-violet, so far as is known, the effective emissions of different cathodes stand in the same order as their true emissions.

Next we have to consider the influence of the type of cell on the magnification. (The type may affect also the emission (page 24), but its influence is relatively unimportant.) In Chapter VI we were concerned with the maximum magnification, and in this matter there are certainly great differences between the various types. But it is important to insist that the maximum magnification is obtainable only in carefully controlled conditions and that, if moderate magnifications are sufficient, they can be obtained with any reasonable type. Makers do not claim generally a magnification of more than 10; and in this they are wise; for, though their cells will actually achieve more, a more ambitious claim would

mislead all but highly-skilled users. If their claims are so limited, they are always justified, whatever the type.

Most cells on the market are intermediate in type between the two extremes discussed in Chapter V, and intermediate in performance. The field due to the potential between the electrodes is more uniform than in the large spherical type, but less uniform than in the plane type. The characteristics are steeper than those of the plane type and the critical illumination of page 83 larger, but less steep and smaller than in the spherical type. We believe ourselves that the plane type is the best, except possibly for very small lights, when the dark current is important; but since most other makers do not adopt it, there must be strong arguments on the other side. They have important advantages when intermittent currents are used with moderate illuminations (see page 159). Sizes differ very considerably as well as types. Good cells are offered in spherical bulbs between 10 and 3 cm. in diameter, and in cylindrical bulbs varying in length from 15 to 3 cm., and in diameter from 4 to 1 cm. Smaller cells are not satisfactory in our experience, and in the smallest of these some sacrifice seems to have been made. Larger cells are only suited for special purposes, and are usually far from uniform over their area.

Considerable variations are also to be found in the glow potential and stopping potential in virtue of different gases and different pressures used for filling. The glow potential in the dark usually lies between 300 and 120 volts, the stopping potential between 200 and 100. Low potentials are often adopted on the ground of convenience; but high magnifications, a long range of linear response, and low critical illuminations (see page 83) are favoured by high potentials. Potentials are generally higher in the spherical than in the plane type.

Although there is thus great latitude in type and size of cell consistent with satisfactory performance, there is much less latitude in the type and size that will give absolutely the best performance in any given circumstances; and again we deprecate the habit of designing apparatus without regard to the photoelectric cell, and then demanding a cell that will fit into some confined space that has been left for it, almost accidentally.

Testing Cells.

The following series of tests, interpreted in the light of our discussions, will enable the quality of a cell for most applications to be judged.

1. Measure the current when exposed to a known light with a potential of 16 volts applied to the cell. This is an indication of the emission.
2. Repeat (1) after passing the glow discharge, unless the cell is known to be damaged by this process.
3. Determine the voltage characteristic with four constant lights of about 0.001, 0.01, 0.1, 1 lumen.
4. Test the insulation and dark current.

Making Cells.

Though commercial cells are now good and not very expensive—the ordinary types are priced at £5 or less—those who are practised in glass-blowing and vacuum technique may prefer to make their own. Those who are not so practised had better acquire their experience in some other field. Elaborate accounts of the process have been published; here we propose to offer only a few hints on matters concerning which doubt might arise.*

For the glass work a borosilicate glass (e.g. Pyrex) is preferable; when the art of handling it has been acquired, it is easier to work than any other glass. Lead glass cannot be used with the alkali metals, which attack it. Lime-soda glass is possible, though some forms crack when sodium is heated in contact with them; it is mechanically weak and liable to crack, but its gravest fault is its high electrical conductivity and the readiness with which it acquires conducting films of moisture.

For silvering we recommend Brashear's solution; it stands the high temperature during exhaustion better than others. Sodium is apt to destroy the silver coating; if it is to be used, it is better to use platinum, or to protect the silver with a layer of electrolytically-deposited copper. The tungsten or

* See E. O. Hulburt, *Astrophys. Journ.*, xli, 400, 915; J. Kunz and J. Stubbins, *Phys. Rev.*, vii, 62 (1916); H. E. Ives, *Bell System Tech. Journ.*, v, 320 (1926); W. B. Nottingham, *Journ. of the Franklin Inst.*, 205, 637 (1928). The method of making potassium on copper cathodes is given in British Patent 306996; that of making caesium on silver oxide cathodes in British Patent 303476.

molybdenum wires sealed through borosilicate glass do not readily make contact with chemically-deposited silver; they should, therefore, terminate internally in a short piece of platinum wire pressed into contact with the glass before silvering. Parts of the cell that are to be kept free from silver and yet must be covered by the silvering solution should be coated with beeswax (not paraffin wax), subsequently dissolved in benzene. If a quartz window is required, it can be attached with cement; a graded seal from quartz to glass is preferable, but the objections to *suivable* cements are not so great as might be anticipated.

It is not necessary to heat the electrodes, in order to remove gas, to a temperature higher than that reached during exhaustion.

The alkali metals (except lithium) and cadmium or zinc are best introduced by distillation from a tube, the bottom of which protrudes from the oven during baking. Sodium, potassium, cadmium, zinc, may be introduced as metal. Rubidium and caesium, which cannot be wasted, are most conveniently introduced as azides, which decompose quietly on heating in vacuo to about $350^{\circ}\text{C}.$; they are not to be decomposed until just before filling. Alternately, they may be generated by heating mixtures of the chlorides with calcium or of the bichromates with the mixture of the rare earth metals known as misch metal. Sodium can be introduced by electrolysis through appropriate glasses, and the same process has been described for potassium; but we are not aware that it has any advantages.*

Many writers place great stress on the necessity for purifying the metals very carefully, e.g. by repeated distillation. These precautions may be necessary as one step in the process of obtaining the metal in its state of highest emission; but it must be remembered that this state is not itself one of great purity; the purest (or at least the most gas-free) state attainable is almost completely insensitive to the visible spectrum (see page 30). Some purification can be effected after the metal is in the cell by distilling it from one

* The electrolysis of sodium through glass was invented by Warburg (1884); it is used in the Burt cell. (See R. C. Burt, *Phil. Mag.*, xlix, 1168 (1925). For the corresponding method with potassium see British Patent 271116. A method of introducing lithium into cells is given by E. Seiler, *Astrophys. Journ.* lii, 129 (1920).

part to another. The parts that have to be free from the metal are, of course, cleared by heating, so that the last layer deposited is almost always one distilled in this way. The great variations in emission between cells prepared in apparently exactly the same way are probably connected with the exact conditions prevailing when the metal is finally driven into its proper place.

The hydrogen used for sensitizing should be free from nitrogen, but a trace of oxygen is not serious. A palladium tube, such as was used on gas X-ray tubes, is the easiest method of introduction. The pressure and current during sensitization can vary within wide limits without making much difference to the results; we prefer nearly the highest pressure at which the discharge will cover the whole cathode. There is often no advantage in continuing the discharge after the full colour change has occurred; but we are not prepared to say that the time of the discharge may not sometimes be important. Trial is here the only guide; the final activity is not attained until many hours after the discharge, and readings taken immediately after it may be misleading. No very great care is needed to pump away the last traces of hydrogen before filling with neutral gas.

The usual filling gases are argon and the mixture of neon and helium from air. Argon gives the lower glow potentials, but is less easily purified. Commercial argon usually contains more than 10 per cent of nitrogen, which may be removed easily by arcing with a cathode of misch metal in an iron cup. Here, again, great weight is usually laid on the purity of the gas; but we know of no evidence that extreme purity is essential. The pressure is fixed largely by the glow potential desired. On this matter see page 61; of course, it must never be so low that the current tends to saturation at high voltages.

PART II

THE USE OF PHOTOELECTRIC CELLS

CHAPTER IX

SOME GENERAL PRINCIPLES

Detection, Comparison, and Measurement.

THE objects and methods of using photoelectric cells are many and various. But there are certain elements common to all of them. It will save time if we begin with some very general considerations, although they may seem at first sight too abstract for a practical handbook.*

In every application we are concerned with variations in some ultimate cause L , which is related to variations in some immediate effect y through the action of the photoelectric cell and its subsidiary apparatus. Thus L may be the luminous flux from a lamp, y the position of a spot on a galvanometer scale; or L the reflecting power of some object scanned in television, y the brightness of a neon tube; or L the colour of an indicator in volumetric analysis, and y the note in a telephone; and so on. By studying the possible forms of the relation between L and y we can classify the objects of various applications and the methods available to attain them, and can establish criteria to decide how far each class of method is suitable for each class of object.

We begin with objects. These we may classify as detection, comparison, and measurement. Our object is detection, if we merely wish to distinguish whether L lies within or without certain limits; it is comparison, if we wish to decide whether one L is the same as some other L ; it is measurement, if we wish to distinguish every L from every other different L , and to assign numerals to represent the differences. The achievement of these three objects imposes

* For a comprehensive description of the principles underlying all measurement, perhaps we may refer the reader to N. R. Campbell, *Measurement and Calculation* (Longmans, Green & Co., London, 1928).

conditions of progressively increasing stringency on the relation between L and y . If the object is detection, it is sufficient that every y corresponding to an L within the limits is distinguishable from every y corresponding to an L without them. If it is comparison, it is necessary further that no two L 's should correspond to the same y , but it is not necessary that no two y 's should correspond to the same L . Measurement consists in measuring y and making use of a numerical law between L and y ; then the relation between L and y must be expressible mathematically by an analytic function or graphically by a smooth curve, and (in practice) the function or the curve must have one of a few simple forms.

The recognition of these differences is important, because greater stringency in one direction often necessitates less stringency in another, or at least some loss of convenience. If our object is measurement, we cannot expect the latitude of choice possible in detection; if, on the other hand, we merely want to detect, it is unwise to hamper ourselves by the limitations required for measurement.

But though the three operations are distinct, both comparison and detection can lead to measurement. Thus, if we have at hand a sufficiently large collection of systems of which the L 's have already been measured, we can measure any other system by comparing it with the standard systems and deciding which of them has the same L . Again, detection can usually be associated with control; y can consist in the operation of some mechanism which is started or stopped according as L falls within or without the limits; almost all the problems of detection that we have to consider are really problems of automatic control. Now the mechanism controlled can often be arranged to alter L so that it falls at the boundary of limits, measure it by the amount of alteration required, and to record the measurement. Many problems of measurement are thus really problems of comparison or of detection; more than a superficial analysis is required to classify them. We shall often use the term measurement, for the sake of brevity, to include both comparison and detection when no confusion is likely to arise; but we hope to preserve the distinction whenever it is material.

Sensitivity.

We now turn from objects to methods. These are distinguished by the nature of their y 's, and of the intermediaries connecting them with L . But before we discuss this aspect, let us consider some desirable qualities of methods.

Whether the object be measurement, comparison, or detection, an important quality of the method is *sensitivity*. This word is often used loosely with many slightly different meanings; when a precise and definite conception is required it is better to use the *sensitivity limit*. (It is unfortunate that the smaller sensitivity limit corresponds to the greater sensitivity in the ordinary sense; but this anomaly is unavoidable except at the expense of verbal clumsiness, and, once it is observed, need cause no confusion.) The sensitivity limit (ΔL) of a method of detection is the least difference between two L 's lying on opposite sides of the limit of detection; of a method of comparison, the least difference between two L 's that can be judged different; of a method of measurement, the least difference between two L 's to which different numerical values are assigned. The conception may be usefully extended also to the y 's, and to any magnitudes intermediate between L and y in the chain of cause and effect. Thus the sensitivity limit (Δy) of y is the least difference between two y 's that can be directly distinguished; and if y is the scale reading of a galvanometer actuated by the currents through the cell due to its illumination, Δi is the least difference between two currents that the galvanometer will distinguish.

These sensitivity limits for a given method are, of course, related, though not so simply as might appear at first sight.

It is not always true, e.g., that $\Delta L = \Delta y \cdot \frac{dL}{dy}$, where dL/dy is determined by the average rate of change of L with y . For the change of y with L is not always perfectly regular; if the value of y corresponding to the same L is determined repeatedly, slightly different values of y will usually be obtained. If $\Delta_2 y$ is the extreme difference of the y 's corresponding to the same L , it is not really possible to distinguish between L 's differing by $\Delta_2 L = \Delta_2 y \cdot \frac{dL}{dy}$. If $\Delta_2 y$ is greater

than Δy , the *effective* sensitivity limit is greater than the *ideal* sensitivity limit $\Delta_1 L = \Delta y \cdot \frac{dL}{dy}$, and must be distinguished from it; the true ΔL is the greater of $\Delta_1 L$ and $\Delta_2 L$. This is very important. For Δy is determined by the type of indicating instrument and the class of method employed; when this is fixed, $\Delta_1 L$ decreases as dy/dL is increased; hence in comparing methods of the same class, dy/dL is sometimes called the sensitivity of the method, and it is suggested that an increase in dy/dL is necessarily an improvement in effective sensitivity. But this is not so: for $\Delta_2 y$ almost always increases with dy/dL ; $\Delta_2 L$ cannot be reduced, and may even be increased, by increasing dy/dL . No increase in precision results from increasing dy/dL beyond the point where $\Delta_2 L = \Delta_1 L$, and the effective sensitivity limit is determined by the irregularity as much as by the sensitivity limit of the indicating instrument.

Accuracy.

Just as we have distinguished ideal and effective sensitivity, so we must also distinguish accuracy from sensitivity. Inaccuracy, sometimes called systematic error, arises when the assumptions underlying the method (namely, that the conditions of page 98 are fulfilled) are not strictly true. It is most frequent and most serious in measurement when it involves the assumption that the law relating y and L has some particular form, e.g. that it is linear. It may also occur in comparison; for disturbances, e.g. a change in the emission of the cell, may lead to regular variations of y for a given L ; or it may arise in the part of the chain of cause and effect prior to L . In detection it is seldom important. Inaccuracy may be masked by insensitivity; if the greatest error E in determining L from y due to a failure of the assumptions is less than the effective sensitivity limit (ΔL), then inaccuracy is unimportant. Otherwise, since it is always avoidable by a suitable choice of method, it ought never to be tolerated unless precision (which is the result of sensitivity and accuracy) is being deliberately sacrificed to some other desideratum, such as speed or simplicity of apparatus.

The sensitivity limit and the error depend on the magnitude

of L as well as on the method of measurement, comparison, or detection; in general they increase with that magnitude. On the other hand, $\Delta L/L$ and E/L , which may be called the relative sensitivity limit and relative error, generally decrease as L increases. But there are important exceptions to both these statements.

Null Methods.

Particular advantages often attach to methods of detection in which a value of y at or near zero forms the boundary between the two ranges to be distinguished, and to methods of comparison in which such a value is made to correspond to the standard with which the comparison is to be made. One of these advantages is increased sensitivity of the kind that results from a suppressed zero in a direct reading instrument. Thus, if we compare resistances by means of a bridge rather than by the deflection of a galvanometer carrying the full current passing through the resistance, we are enabled to use a more sensitive galvanometer. But there is also a gain in the kind of sensitivity that results from regularity, because the variations of the battery voltage are eliminated; this gain arises from the choice of a suitable method of compensation in order to reduce the reading to zero.

Strictly speaking, there is no such thing as a null method of measurement; for if we are to deduce varying values of L from the values of y , y must vary. The distinction between null and direct reading methods lies in the choice of the magnitude which plays the part of y . Thus in the direct reading method of measuring resistances, y is the deflection; in the null method, y is the resistance inserted in the compensating arm of the bridge, the deflection being reduced to a condition determining which value of y is to be taken as corresponding to L . The substitution leads to a gain in sensitivity, as it does in the associated methods of detection and comparison; but the more important gain is in accuracy. There is no difference in accuracy between the two methods we are considering if they are used strictly for comparison; if the resistances to be compared are always inserted in the same place in the testing circuit, equal resistances are strictly equivalent whatever the circuit. But in measurement the balancing arm of the bridge ceases to be a mere

compensator; it provides the standard. The bridge is more accurate than the direct reading method, because the law that the resistances in corresponding arms are proportional is more nearly true than the law that the resistance is inversely proportional to the deflection.

This gain in accuracy is not a necessary consequence of using a null method; it is a consequence of using a particular null method in which the result of compensation is the substitution of a more accurate for a less accurate law between L and y . If they have not this feature, null methods lose all their merit in measurement. A general rule can be framed by which it is usually possible to decide how far a proposed null method possesses this necessary feature; it is that a method of measurement is the more likely to be satisfactory the more nearly it approaches to comparison, and the more nearly the compensating magnitude resembles that to be measured. The bridge method of measuring resistances is so valuable because the compensating magnitude is also a resistance; when the ratio arms are equal, measurement by inserting an equal resistance in the compensating arm comes very close to comparison by substituting it in the same arm.

Classification of Methods.

Let us now classify methods in another and, perhaps, more directly practical way, namely, by the nature of L and y and their intermediaries.

First, we note that one link in the chain must always be the quantity of light entering the cell; for it is this that determines all changes in its characteristics. We shall break the chain at this point, and regard as distinct questions how the ultimate cause L determines this quantity of light, and how the quantity of light determines the immediate effect. The first question is really that of the various applications which can be made of photoelectric cells, and the kind of problem that they can be used to solve; it will be the subject of Part III. The second is that of the ways in which photoelectric cells can be used in order to solve these problems.

For the remainder of this part then L is the quantity of light entering the cell, and we have to consider only the relation between this quantity and the immediate effect y .

In the great majority of ways of using cells, one link between our new L and y is the current passing through the cell under a constant (or nearly constant) voltage; all these ways of using cells reduce on analysis to ways of measuring current. Methods of measuring current fall naturally into two main groups, according as they employ electromagnetic or electrostatic instruments. Accordingly, classes into which methods of using photoelectric cells fall naturally are (1) methods in which current is measured electrostatically, (2) methods in which current is measured electromagnetically, (3) methods in which some characteristic of the cell is measured other than the current under a constant voltage. These three classes are the subjects of the following three chapters.

The Compensation of Current.

Any matters common to all methods should, however, first receive our attention. Most of these are too trivial to mention; but a word may be said about a problem common to all methods of measuring current, namely, the use of compensating arrangements which convert direct-reading into null methods.

In measuring currents in circuits containing ohmic resistances only, it is usual to compensate by another ohmic circuit; the various types of bridge are based on this principle. This type of compensation may be applied to photoelectric cells by means of the circuit of Fig. 23; the current in the compensating circuit is varied by means of R or E , until no current flows to the indicating instrument G . An obvious development would convert the circuit into a 4-arm bridge, of which the cell would form one arm, but little would be gained thereby. For according to the general rule of page 102, this form of compensation, though right for ohmic circuits, is wrong for those that are not ohmic; and actually its useful applications are very limited (cf. page 113). The special merit of the bridge arrangement, namely, independence of the battery voltage, is not obtained when one of the arms of the bridge is not an ohmic resistance.

The more generally useful forms of compensation are those in which the compensating current is also of photoelectric origin. Here, then, are two possibilities; the currents that

are balanced against each other may come from different cells, or they may come from the same cell. In either case the balance is effected (for the main part at least) by adjusting the lights that produce the currents.

The circuit appropriate to the first alternative is shown in Fig. 24, G being as usual the current-indicating device, and r protective resistances (see page 64); it is essentially a bridge. If the two cells have the same voltage characteristic and are used at the same voltage, the balance will be independent of small variations in the battery voltage. Even if they

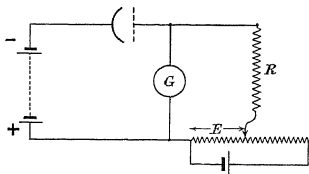


FIG. 23. COMPENSATION METHOD
USING OHMIC RESISTANCE

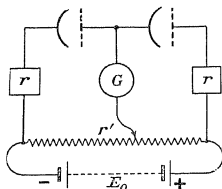


FIG. 24. COMPENSATING CIRCUIT
USING TWO CELLS

have not the same characteristic, the use of a common battery shunted by r^1 makes the balance less liable to accidental fluctuations than it would be if separate batteries were used. If constancy of the battery can be ensured, r^1 may be used in another way, namely, as a fine adjustment of the balance; a movement of the sliding contact will displace the balance while the lights received by the two cells are constant. This method of adjustment is especially useful if vacuum cells are used and the photoelectric currents are nearly saturated. Indeed, the whole circuit is primarily adapted for vacuum cells; for it is not easy to find pairs of gasfilled cells sufficiently well matched in their characteristics to give the advantages that the method should possess. In particular it should be noted that, since the characteristic of a gasfilled cell varies with the illumination, a pair of cells matched at one illumination may not be matched at another, and that even when the arrangement has been adjusted at one illumination so that a balance indicates equality of lights falling

on the cells, balance at another illumination may not indicate equality.

In the alternative arrangement, when the balanced currents come from the same cell, the lights (though they may come ultimately from the same source) are thrown alternately on the cell by a rotating mirror or shutter. The current indicator G is placed in series with the cell and its battery (Fig. 31, page 130), and has to be one that responds only to a fluctuating current, showing no deflection when the current is constant. An obvious method of securing such an indicator is to pass the current through the primary of a transformer to the secondary of which some form of alternating-current ammeter (e.g. a valve amplifier and rectifier) is connected. But it can also be secured by means of a commutator driven synchronously with the rotating mirror or shutter.*

In a device of this kind the commutator reverses the connections of a galvanometer to the cell when the change of illumination occurs. Consequently, the two illuminations deflect the galvanometer in opposite directions; their equality is indicated by an absence of steady deflection. There will be some vibration of the instrument about its zero; this can be reduced without limit by running the commutator fast enough, or by applying a compensating current nearly equal to that produced by the illumination. The shutter has to be very carefully made so that each of the illuminations is applied for exactly the same fraction of the period of rotation, and so that each is cut in and out in exactly the same way.

The need for this condition is eliminated in another arrangement. Here the current from the cell passes through the primary of a transformer, to the secondary of which the galvanometer is connected. The connections of the galvanometer are now reversed when the shutter is fully opened and the illumination is constant; they are complete during the change of illumination. The galvanometer thus receives successive impulses in the same direction, proportional to the total change in illumination due to the substitution of

* L. Bohr, *Journ. Opt. Soc., America*, x, 288 (1925); Clayton Sharp and C. Kinsley, *Trans. Am. Ill. Eng. Soc.*, xxi, 117 (1926). A method that dispenses with the commutator is described in U.S. Patent 1672672.

one illumination for the other; the rate and manner of change is immaterial, so long as it takes place in a period short compared with the time constant of the transformer and galvanometer. The direction of the steady deflection representing the sum of these impulses changes according as one illumination or the other is the greater.

The difficulty with both these methods lies in the commutator, which is liable to changes of resistance and parasitic contact or thermoelectric E.M.F's. It is particularly serious when the commutator is to be applied to the output of amplifiers, for the disturbances may be of high frequency and amplified more than the main potentials. Positive are better than sliding contacts; but nobody appears to have succeeded in obtaining from the device the advantages that belong to it in principle.

CHAPTER X

ELECTROSTATIC METHODS

General Theory.

THE foundation of all electrostatic methods of measuring current is the electrometer. It consists essentially of a pair of conductors supported on insulation of very high (ideally infinite) resistance, and capable of moving under the electrostatic forces arising from a difference of potential between

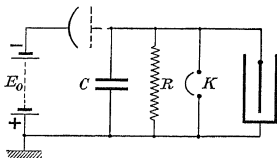


FIG. 25. MEASUREMENT OF PHOTOELECTRIC CURRENT
BY MEANS OF AN ELECTROMETER

them. The simplest form is the simple gold leaf electroscope, in which the potential difference is applied between the insulated gold leaf and the surrounding case; and in order to fix our ideas, it will be convenient to distinguish the two conductors as the *leaf* and the *case*, the leaf being the insulated conductor and the case that maintained at a constant potential in relation to earth. When more elaborate forms of electrometer are described, it will be pointed out which parts perform the functions of leaf and case.

Fig. 25 shows the essential parts of any arrangement for measuring photoelectric currents by means of an electrometer. The anode of the cell is here shown connected to the leaf; nothing would be altered if the cathode were connected to the leaf and at the same time the battery E_0 were reversed. When the switch K is opened, the conductor, consisting of one electrode of the cell, the leaf of the electrometer, one plate of the condenser (if any) and the connections between them,

receives the photoelectric current i flowing through the cell; if C is the capacity of this conductor relative to the remainder of the apparatus, the potential E , indicated by the electrometer, begins to rise at a rate given by

$$C \frac{dE}{dt} = i \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

so that

$$E = \frac{it}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

But as soon as E becomes finite, part of the current flows away through the resistance, and we have

$$C \frac{dE}{dt} = i - \frac{E}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

so that

$$E = Ri \left(1 - e^{-\frac{t}{t_0}}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where $t_0 = RC$.

In the final state all the current flows away through the resistance, and E assumes the steady value

$$E = Ri \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

E in (19) is the greatest reading of the electrometer that the current i can produce, and the ideal sensitivity limit of the apparatus is, therefore, $\Delta i = \Delta E/R$, where ΔE is the smallest change of potential the electrometer will show. R is greatest when it represents nothing but the unavoidable leak of the most perfect insulation that can be used to support the insulated electrodes; it may then be as great as 10^{14} ohms. ΔE need not be greater than 0.001 volt, so that Δi may be as low as 10^{-17} amp. A gasfilled cell may give as much as 10^{-4} amp/lumen, so that 10^{-13} lumen, or the light received on 1 sq. cm. from a candle 30 km. distant, might be detected. But such sensitivity is not really practicable; for the deflection corresponding to E in (19) would not be attained until after a time much greater than t_0 ; C will not be less than $50 \mu\mu F$, and therefore t_0 not less than $10^{14} \times 50 \times 10^{-12}$ sec. = $1\frac{1}{2}$ hours. This calculation is given merely to indicate the order of the magnitudes with which we may be concerned here; we will now turn to the conditions of practical use.

Rate of Deflection Methods.

The most usual direct-reading methods of electrometer measurement are based on (16). For an absolute measurement, the three magnitudes E , C , t must be determined; but in relative measurements, two of them may be constant and the third determined. In the *constant voltage* method, E and C are constant, and the time required for the current to charge the electrometer to a fixed potential is determined; i is inversely proportional to this time. In the *constant time* method, C and t are constant, and the potential attained in a fixed time is determined; i is proportional to this potential.

Both methods have their virtues and defects. The constant voltage method requires no calibration of the scale of the electrometer, which is often not even approximately linear; the calibrated instrument is a stop watch or chronograph. On the other hand, the constant time method is suitable for automatic registration; for a mechanism can easily be devised to allow the current to flow for a fixed time, and then record the reading of the electrometer. The constant voltage method cannot be used if the electrometer has appreciable inertia, so that the reading does not correspond to the simultaneous voltage; in the constant time method, the instrument can be allowed to come to rest before the reading is taken.

In the constant time method there is no limitation, in principle, to the sensitivity other than that which has been noted already; for, according to (18), i is always proportional to E , for a given t , however large t may be. On the other hand, the sensitivity of the constant voltage method is limited by accuracy; for (16) is not valid, and i is not inversely proportional to t , unless t is small compared with t_0 . The limitation thus imposed is the more serious the greater the difference between the currents to be compared. With sufficient approximation we have

$$\frac{i_1}{i_2} = \frac{t_2}{t_1} \left(1 - \frac{E}{2R} \frac{i_1 - i_2}{i_1 i_2} \right) \quad . \quad . \quad . \quad . \quad . \quad (20)$$

The expression in brackets must not differ from 1 by more than the permissible error; that is to say, if an accuracy of x per cent is required, it must not differ by more than

From (21) we may derive also a formula, similar to (20), for the error incurred by the use of the constant time method; it is

$$\frac{i_1}{i_2} = \frac{E_1}{E_2} [1 + \frac{1}{2}\gamma (E_1 - E_2)] \quad (22)$$

The *relative* error thus depends on the difference between the *absolute* values of the extreme voltages observed. For 1 per cent accuracy, this difference must not exceed 1 volt if $\gamma = 0.02$, nor 0.2 volt if $\gamma = 0.1$. There is no limit in either direction to the magnitude of the currents, so long as the fixed time and the capacity are chosen so as to reduce the extreme voltages observed within these limits; since an increase of capacity will always result in a reduction of the voltages, no difficulty need ever be experienced in fulfilling the condition; on the other hand, an electrometer with a low sensitivity limit for voltage may be required in order that voltages within the narrow range imposed by accuracy may be distinguished.

If the conditions for accuracy are fulfilled, the precision is determined by the sensitivity limits Δt , ΔE in the measurement of time and voltage; these may be taken as independent of t and E .

From (16)

$$\frac{di}{i} = \frac{dE}{E} - \frac{dt}{t} \quad (23)$$

In estimating Δi , the maximum uncertainty in i , we must suppose that the errors in E and t are in such direction that their effects are added; consequently

$$\frac{\Delta i}{i} = \frac{\Delta E}{E} + \frac{\Delta t}{t} \quad (24)$$

In the constant time method, it is always possible to arrange that the second term is inappreciable compared with the first; hence the relative sensitivity limit decreases as the current measured increases. In the constant voltage method it is less easy to ensure that the first term is negligible, for there may be a ΔE representing a possible shift of the electrometer zero between observations; but the term will be

constant, and the relative sensitivity limit will increase, like the second term, with the current.

Steady Deflection Method.

A third possible direct-reading method is based on (19); the switch is kept open until a constant reading of the electrometer is attained; this reading is proportional to the current. This may be regarded as a variant of the constant time method in which the time chosen is long compared with t_o , so that its exact value is immaterial. It is essential that the resistance R should be constant; the insulation leak is never very constant; for this reason, and also in order that the time required for an observation may be kept within reasonable limits, it is necessary to insert an artificial leak of resistance R_o , small compared with the insulation resistance R and in parallel with it. The sensitivity is necessarily reduced greatly. If a reading is not to occupy more than 1 minute, t_o must not be more than 12 seconds, if 1 per cent accuracy is sought; consequently, if C is as low as $20 \mu\mu F$, R must not be more than 6×10^{11} ohms, and the sensitivity limit for current will not be much less than 10^{-14} amp. This is certainly greater than the sensitivity limit attainable in the measurement of small currents by either of the other methods; the steady deflection method is useful only when rapid changes in comparatively large currents have to be followed with comparatively little precision. R and t can then be much less than the value just suggested. It should be noted that, if gasfilled cells are used, the maximum voltage must be limited in the same way as in the constant time method.

Null Methods.

The precision of all these direct-reading methods of measurement is small, being limited partly by sensitivity and partly by accuracy; it is not easy to avoid uncertainties of 1 per cent. In comparison, their precision is somewhat greater because accuracy is no longer essential, and with carefully-designed apparatus currents differing by only 0.1 per cent may be distinguished. The best of the methods for this purpose is, undoubtedly, the constant time method with automatic timing and permanent registration (see

page 109); it combines speed and precision, but demands a somewhat elaborate equipment. On the other hand, most of the difficulties that we have been discussing disappear if null methods are used; they are so simple, and so much more trustworthy than any direct-reading method employing an electrometer, that they should always be used unless precision is quite unimportant, or unless the special circumstances forbid even the slight additional elaboration of the apparatus that they demand.

Either of the first two methods described on pages 103-106 may be adopted; that which involves a commutator is not suitable. The leads to G in Figs. 23 and 24 are represented by the leads to the leaf and earthing switch and to the case; a balance is attained when the electrometer does not begin to charge up if the switch is opened.

When compensation is by means of an ohmic resistance R_o , the sensitivity limit for current is E/R' where $1/R' = 1/R_o + 1/R$; in order that there may be no sacrifice of sensitivity, R_o must not be small compared with R . The objections to a large value of R_o in the steady deflection method, which is closely similar, are no longer serious, because there is no need to wait until the deflection becomes steady before taking a reading. But, actually, resistances greater than 10^{11} ohms (which is much less than the insulation resistance should be) are not often employed, because it is difficult to obtain such resistances obeying Ohm's Law. The method is valuable when currents of the order of 10^{-11} amp. or more have to be measured, but is not to be recommended for very small currents.

The second of the two general methods, namely, compensation by the current from another photoelectric cell subject to a controlled illumination, is entirely suitable, even for the smallest currents; it has been used successfully for many purposes. But there may be some difficulty about calibration when the absolute magnitude of the current has to be known, or sometimes even when merely relative values are required. A proposal for overcoming this difficulty by substituting a thermionic for a photoelectric compensation is just worth mentioning.*

The best method in these circumstances is usually one

* Research staff of the General Electric Co, *Journ. Sci. Inst.*, i, 56 (1923).

not mentioned in the preceding chapter, because it is suitable only in conjunction with an electrometer. This is compensation by electrostatic induction (Fig. 26). As the insulated electrode charges up with the current through the cell, its potential is reduced to zero by inducing on it an equal and opposite charge through the condenser C_o , of which one plate is connected to the leaf, by raising the potential E_o of the other plate by means of a potentiometer. (C is now the unavoidable capacity of the leaf, and its connections; R is the insulation resistance.) In this procedure the switch is opened when $E_e = 0$; the light is then

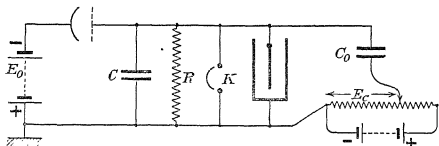


FIG. 26. COMPENSATION BY ELECTROSTATIC INDUCTION

thrown on the cell by means of a shutter for a period t . During this period the electrometer is kept near zero by means of the potentiometer, in order to reduce insulation leaks to a minimum. After the shutter is closed again, it is adjusted accurately to zero. If E_e is the final reading, $i = E_e C_o / t$. The only calibration required is a measurement of the capacity C_o , which is permanently stable if the condenser is properly made; the same condenser can be used in different experiments. If small currents are to be measured, C_o should be small compared with C , in order that the speed of the measurements should not be reduced, and a wide range obtained by using large values of E_e . This is an admirable method, which is not used as widely as it ought to be; but the necessity of turning the light on for accurately timed intervals is sometimes, though not often, an objection.

Vacuum and Gas-filled Cells.

In both of the last two methods of compensation, the ideal sensitivity limit of current is the maximum obtainable,

Then Fig. 27 gives the factor of ΔE in (26) plotted against L ; this factor determines the sensitivity limit if the electro-

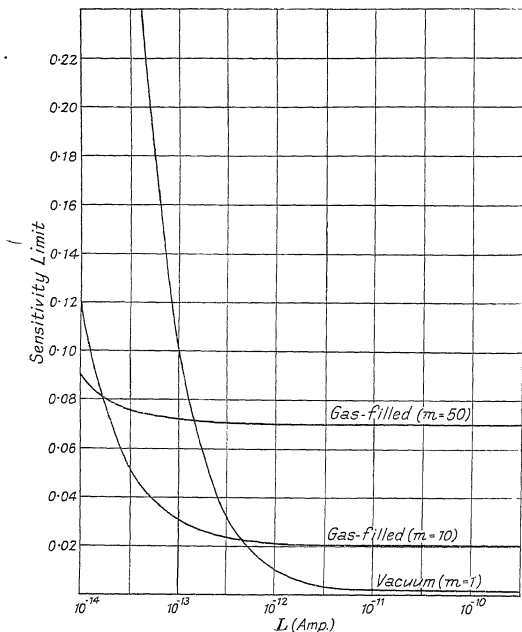


FIG. 27. VARIATION OF SENSITIVITY LIMIT WITH ILLUMINATION

meter is always the same. (For convenience, L is plotted on a logarithmic scale.)

If L is greater than 10^{-12} amp., the limit for the vacuum cell is less, and the sensitivity is greater, than for the

gas-filled cell ; for smaller currents, the gas-filled cell used with $m = 10$ is more sensitive than the vacuum ; but an increase of m to 50 makes the cell less, and not more, sensitive unless L is nearly as small as 10^{-14} . We see then, as our general argument indicated, that in compensation methods gas-filled cells, especially used at high magnifications near the glow potential, are not more, but less, sensitive than vacuum cells, unless the illumination is very feeble. For even when $L = 10^{-11}$, the illumination is still too small to be indicated at all on an ordinary galvanometer, even when a high magnification is used in a gas-filled cell ; and $L = 10^{-12}$ means an illumination less than is likely to occur in any of the more usual applications, except stellar photometry. In the photometry of lamps and the measurement of absorption in the visible spectrum, to which compensation methods have been often applied, L is more likely to be of the order of 10^{-9} or even 10^{-8} .

Perhaps this comparison has been made unduly favourable to the vacuum cell. Thus 10^{-14} mho is a rather small value for I' ; it can be attained by careful attention to the insulation, but, in general, it is likely to be rather higher. If it were 10^{-13} mho, a comparatively high value, vacuum cells would not be more sensitive unless L were as great as 10^{-11} amp. Again the speed of observation is greater if gas-filled cells and, therefore, larger currents are used ; speed increases regularity, since irregular changes in the electrometer zero are less important, and thus increases the real, as distinct from the ideal, sensitivity. But this ideally greater speed will not be effective if L is greater than 10^{-11} amp ; for a current of that magnitude charges a capacity of $50 \mu\mu$ F. to 0.1 volt in $\frac{1}{2}$ second, which is less than the period required for an observation.

On the other hand, vacuum cells have advantages of their own that have not been taken into account. They are much more regular in their action, their sensitivity is more independent of their previous history, and, since their current is nearly saturated, constancy of the battery potential E_0 is less important. These features tend to make the real approach the ideal sensitivity. In short, vacuum cells should be regarded as normally most suitable for null methods using an electrometer ; there may be circumstances, such as

imperfect insulation or very small illuminations, in which gas-filled cells have the advantage, but they should not be used unless there is definite positive evidence that these circumstances have arisen.

One further remark should be made in order to avoid misunderstanding. Since the greater current sensitivity of gas-filled cells does not make them preferable to vacuum cells, it might be concluded rashly that variations of current sensitivity in cells of the same class are unimportant. But in our comparison we have supposed that the photoelectric emission is the same in the vacuum and gasfilled cell; increased current sensitivity arising from increase in the emission is always desirable.

Electrometers.

We now turn from principles to practice. The technique of electrostatic methods is not as familiar as that of electromagnetic methods, and some account of it may be useful.*

All electrometers are descended from one or two ancestral strains, the electroscope with diverging gold-leaves and the Thomson quadrant electrometer. In recent years the strains have crossed, and instruments have appeared with some of the characteristics of both; but they are still quite distinct. In electrometers of the first kind, the "leaf" is the moving system, and sensitivity is sought by making it as light and flexible as possible. In those of the second kind, the "leaf" is part of the fixed conductor (for the "idiostatic" arrangement is never used), the moving part is relatively massive, and sensitivity is sought by increase of the electrostatic forces, obtained by the application of subsidiary potentials. The typical characteristics of the first kind are rapidity and simplicity; of the second kind, sensitivity and ease of observation.

The only surviving member purely of the first kind worthy of mention is the "ticking electroscope" mentioned below; in all other modern instruments subsidiary potentials are employed. But there is a large and important group possessing the characteristics of this kind. The essentials of their

* A very good account of electrometer technique is given in Rutherford's *Radioactive Substances* (Cambridge University Press, 1912); but it is slightly out of date.

construction are shown in Fig. 28. A very light conductor L , which is usually either a gold leaf or a Wollaston wire or a quartz fibre rendered conducting by a metallic coating, lies between two plates P maintained at equal and opposite potentials from earth or, more accurately, from the potential of L when the earthing switch is closed. The equilibrium of L is unstable in respect of the electrostatic forces from the

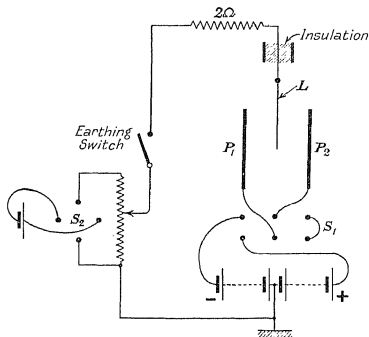


FIG. 28. TYPICAL ELECTROMETER CIRCUIT

plates, and, if these acted alone, L would fly to one plate or the other; stability is given by the weight of L , and sometimes by elastic forces due to a spring attached to its lower end. The two sets of forces are nearly balanced, leaving a slight margin of stability; the less this margin the greater the sensitivity. But the balance never extends equally over the whole space between the ends; if there are no elastic forces, instability will enter when the deflection is too large. The deflection of L is not proportional to its potential above earth except over a small central range. It may be observed either through a microscope or preferably by projection on a screen. Since many experimenters are not as familiar with projection as with galvanometer spots, it may be recorded that an image magnified at least

20 times and visible from a distance, without shading, in a well-lighted room can be obtained with a microscope objective of 1 in. focus, if a 24-watt motor-car headlight with a condensing lens 3 in. in diameter is used as illuminant.

Elaborate and expensive instruments of this type are on sale; and, though we have no experience of them, we have no doubt that the elaboration and expense is counter-balanced by ease of adjustment and use, for which instructions will be furnished by the makers.* But since much simpler instruments are serviceable, some notes for the home-constructor may be useful. He will be wise to avoid quartz fibres, unless he has previous experience of them; for though they are probably more sensitive than any other form of leaf, the formation of a permanent conducting layer and the mounting of the fibre are very difficult. Gold-leaf is an alternative, but is not pleasant to observe; a carbon filament (still obtainable from lamp makers), hung by a gold-leaf hinge, is preferable, and not very difficult to make; Wollaston wire involves an appreciable sacrifice of sensitivity. A good substitute proposed recently is a straight, fine wire supported at its *lower* end, so long that the gravitational and elastic forces nearly neutralize each other, and the wire nearly, but not quite, bends over under its own weight; a plane loop or hairpin is still better because it will deflect only in one plane. Tungsten is probably the most suitable metal for the wire, but others might serve.† The defect of this device is that the instrument is very sensitive to changes of level.

The case of the electroscope should be made as small as possible, and should be lagged thermally, for convection currents disturb the leaf. The distance between the plates should be roughly adjustable; the position of the support of the leaf *L* relative to the plates should be finely adjustable. The potentials of the plates will be of the order of ± 50 volts; it is not essential that the potential of the plates should be precisely equal. A grid leak of 2 megohms should be placed between the leaf and the key (as shown) to

* E.g. The Cambridge Instrument Co., Ltd., and E. Leybold's Nachfolger A. G., Cologne.

† The tungsten wire electrometer is described in British Patent 284395. See also E. Perucca, *Zeits. f. Instrumentenkde.*, xlvii, 524 (1927).

protect the leaf if it touches a plate. In adjusting, the plates should first be placed far apart and the leaf moved until, when the potential is applied to them, the leaf does not move; for this purpose the switch S_1 is useful. The sensitivity is then tested by applying about $\frac{1}{2}$ volt to it by means of switch S_2 . If it is not sufficient, the plates should be brought nearer and the adjustment repeated. The greatest practicable sensitivity is reached when the potential of $\frac{1}{2}$ volt throws the leaf beyond the range of stability, so that it flies over to one plate. A large distance between the plates and a high potential gives rather greater sensitivity than a small distance and a small potential; but there is a considerable range in which distance and potential may be adjusted to each other to give the same sensitivity.

A voltage sensitivity limit of 0.01 volt may be obtained easily with these instruments, the time of the (completely damped) swing of the leaf being less than 1 second. The capacity will be about $10 \mu\mu\text{F}$.

Of the second kind of electrometer the Compton is the modern form, having replaced the Dolezalek, which was the first notable improvement. Like its prototype it has an 8-shaped needle, carrying a mirror, which is maintained at about 50 volts above earth and rotates in a box divided into quadrants, of which one pair is permanently earthed, while the other is insulated and corresponds to the leaf of Fig. 28. No amateur is likely to try to build this instrument; accordingly reference can be made to the maker's pamphlet for its special features and its adjustments.* A voltage sensitivity limit of less than 0.001 volt is easily attained, the period of swing being 9 seconds and the capacity about $10 \mu\mu\text{F}$.

The long period is a serious disadvantage. As noted already, it makes the constant voltage direct-reading method impossible, and the constant time method very tedious and somewhat inaccurate. For the effective capacity of the electrometer varies with the deflection and, if E is variable in (16), C cannot be assumed constant. The usual substitutes for these methods, when an electrometer with considerable

* The Cambridge Instrument Co.'s catalogue. For Compton Electrometer see A. H. and K. T. Compton, *Phys. Rev.*, xiv, 85 (1919); E. G. Cox and G. C. Grindley, *Journ. Sci. Inst.*, iv, 413 (1927).

inertia is used, are the rate of deflection and the ballistic methods. In the first the switch is opened, and the spot allowed time to take up a constant velocity along the scale; this velocity is taken to be proportional to the rate at which the electrometer receives charge, i.e. $\frac{dE}{dt}$. In the second, the switch is opened for a constant time and the maximum deflection of the spot taken as proportional to the charge acquired; in both cases the factor of proportionality is determined empirically. It can be shown that if certain assumptions about the behaviour of the electrometer are true, either of these methods is legitimate; actually they are not true, and neither method is accurate, unless the assumption of proportionality is abandoned and a detailed calibration undertaken.

On the other hand, the long period is no objection for the steady deflection method; for here it is usually less than the period required for the final value of the potential to be reached. Since here nothing but voltage sensitivity is required, the quadrant electrometer is clearly preferable to the leaf electrometer. Its value in null methods depends somewhat on the temperament of the operator. A naturally slow worker will not be made slower by the extra time that is necessary to decide in which direction the instrument is tending to deflect, and he will be able to make use of its higher ideal sensitivity; a quick and probably impatient observer will do better with the speedier though ultimately less sensitive instrument; for it must be remembered that irregularities are likely to enter if the time occupied in setting a balance is prolonged.

Two of the most important electrometers are hybrids, displaying clearly some of the characteristics of each of the parent types; in mechanical construction they are similar to the quadrant type, but a very light moving system is the leaf and not one of the quadrants. The first is the Lindemann electrometer,* in which the needle is a platinized quartz fibre supported by another fibre at right angles to it, the torsion of which provides the stabilizing forces. The deflection is read by a microscope with or without

* F. A. and A. F. Lindemann and T. C. Keeley, *Phil. Mag.* xlvii, 578, 1924). The instrument is made by the Cambridge Instrument Co.

projection. It was originally designed for use on telescopes, and has the great merit of complete independence of gravity; its small size, though unobjectionable, is not of much importance in laboratory work; it is also relatively cheap. Its demerits are inconvenience of reading—for it is not very well suited for projection—and the fragility that is inseparable from quartz fibres. It requires about ± 30 volts on the plate, and has a sensitivity limit of about 0.01 volts and a capacity of only $2 \mu\text{F}$. In performance, therefore, it belongs to the leaf, and not the quadrant, type.

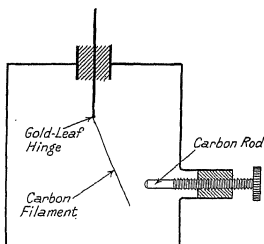


FIG. 29. "TICKING ELECTROSCOPE"

The second is the Hoffmann "duant" electrometer,* in which there is only a single pair of "quadrants" above which moves a light suspended "needle" forming a sector of a circle. It is designed so that the destabilizing electric forces very nearly balance the stabilizing forces. It is certainly the most sensitive instrument known for measuring charge (with the exception of the suspended drops of Millikan and Ehrenhaft); its peculiar properties make it misleading to assign to it a definite capacity and voltage sensitivity, but it has a sensitivity limit for charge of the order of 10^{-16} coulomb, which would be attained by electrometers of other types only if they combined a capacity of $10 \mu\text{F}$. with a voltage sensitivity limit of 10^{-5} volts.

When very rough measurements are sufficient and

* G. Hoffmann, *Ann. der Phys.*, lii, 665 (1917).

simplicity is the primary desideratum, Phillips' ticking electroscope is very convenient.* It is essentially a diverging leaf electroscope of the oldest type, in which the leaf, when it attains a certain divergence, touches the case, is discharged, and collapses. In order that the leaf may not stick when it touches, it is best made of a carbon filament attached to an insulated fixed plate by a gold-leaf hinge, while the part of the case that it touches is the end of a carbon rod carried on a screw by means of which its distance from the plate can be varied (see Fig. 29). If the screw is set so that the leaf touches it when its potential is E (about 50 volts), the leaf will "tick" (i.e. diverge and collapse) n times per second, where $n = i/EC$ and C is the capacity; in practice n should not be more than 2. The method, being a modification of the constant voltage method, is applicable even to gas-filled cells, although much of their magnification is lost, because the voltage across the cell drops E volts during the observation. The instrument cannot be trusted for a relative precision better than 10 per cent.

Insulation.

Insulation is one of the main problems of electrometer technique. The supports of the insulated system connected to the leaf must not only have a very high resistance, but must also be free from electric hysteresis and the tendency to acquire surface charges. The materials generally used in instrument making and electrical engineering—ebonite, rubber, silk, and so on—are quite unsuitable for such supports, though, of course, they may be used where they serve merely to prevent short circuits of batteries. There are only four solids worthy of consideration, amber, sulphur, quartz, and certain waxes or cements; and of these the last two are included with hesitation. Amber is almost universally employed in Germany; if the right material can be obtained and the technique of working it mastered, it is the best of all. Sulphur is as good an insulator, but its mechanical properties are less suitable. It should be cast in place from a temperature just above its melting-point; since it contracts greatly on solidifying, the parts that it separates should be provided with keys, so that the sulphur cannot

* C. E. S. Phillips, *Proc. Phys. Soc. Lond.*, xxxiv, 213 (1922).

slip at its boundaries. Just after solidification sulphur is soft, and can be cut with a sharp tool; later it becomes hard and brittle; but its surface—and insulation leaks are due almost entirely to surface conduction—can be readily cleaned by scraping. Quartz is much stronger than amber or sulphur, and is sometimes convenient in the form of rod or tube; but not all specimens are trustworthy, and we should always prefer amber or sulphur. It must be cleaned by heating to redness and kept clean thereafter.

Of the waxes, we can recommend "Bank of England" red sealing-wax (but not other varieties) and the German black Picein; probably others are equally satisfactory, but we speak of what we know. They are useful for coating other materials, and, in particular, glass. The weakest link in the chain of insulation is (or ought to be) the wall of the photo-electric cell, where the lead emerges; for here glass must be used. The borosilicate glasses, rich in silica (e.g. Pyrex), are much better insulators than soft soda glass; they are preferable for other reasons as a material for cells, but they are improved by a coating of one of these waxes. The waxes should never be heated in the flame, but rubbed on the glass when it is just hot enough to make them run easily.

The smallest possible volume of insulation should be used and mechanical strain avoided, because it develops piezo-electric charges. The insulation is best tested by charging up the insulated system, and observing the fall of its potential. The time required to fall to $1/e$ of the initial value is t_0 of page 108; it should never be less than 15 minutes.

Shields and Switches.

The whole of the insulated system must be enclosed in an earthed metallic case of the smallest possible volume. Leads should be carried through tubes and supported by insulation at the ends only. It is sometimes recommended that the tubes and the lead should be of the same material, in order that voltaic E.M.F's. may be avoided; but this is not necessary if the insulation is good. If the insulated system tends to charge up when it is not connected to the cell, either the insulation is bad or the shielding is insufficient, or some part is not efficiently connected to earth or other fixed potential. A "zero leak" arising outside the cell

should never be tolerated. Earthed guard rings should be inserted whenever the insulated electrode is in solid connection with any conductor not at earth potential.

The leads to the cell, electrometer, condenser, and any other connected parts are best brought independently to a central box containing the earthing switch. The earthing contacts should be of gold or other unoxidizable material; the make and break should not involve scraping, and should not place great strain on the insulation; if these precautions are neglected a troublesome jump of the electrometer will occur when the switch is opened. If the shielding is adequate,

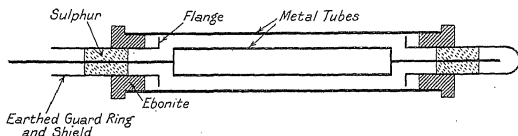


FIG. 30. CONDENSER FOR USE IN COMPENSATION METHOD

Not to scale—about half full size

it is not essential that the “earth” should really be earthed; the “earth” can be any conductor to which all the “earthed” parts are solidly connected.

Condensers.

The condenser used for the compensation method of page 114 must have air (or vacuum) as its dielectric; and so must any condensers that may be introduced (as is sometimes convenient) to diminish the rate of change of potential, if accuracy is required. All solid dielectrics show appreciable hysteresis, which is fatal. Fig. 30 shows a good construction for the compensating condenser, having a capacity of about $6 \mu\text{F.}$; this capacity should be small compared with that of the rest of the system in order that the whole capacity should not be increased. An important element is the flange shielding the insulated electrode from the surface of that part of the insulation which is exposed to the applied field.

Resistances.

Satisfactory high resistances for the steady deflection method or the ohmic resistance compensation method

present a difficult problem. If not more than 10^7 or even 10^8 ohms is required, commercial grid leaks in series provide an entirely satisfactory solution. For still higher resistances several alternatives have been used; to discuss them in detail would occupy too much space; the reader must turn to the references for further details.

The first class consists of thin films of good conductors. Of these the chief are—

Carbon conductors, which may take the form of streaks made by a graphite pencil on ebonite, ground glass, or slate, or of lines of Indian ink ruled on paper. (It is not quite clear whether these last owe their conductivity to the carbon in the ink or to the liquid, often containing glycerine, in which it is suspended.*)

Platinized quartz fibres usually prepared by cathode sputtering. References have been made recently in German literature to resistances of platinized amber, which are presumably made by the same process; but we have not been able to learn details.†

Alkali metal films, especially of rubidium, which form spontaneously on clean glass surfaces exposed to the vapour of these metals (see page 4).‡

The second class consists of substantial portions of very bad conductors. In most of these, if not all, the conduction is probably electrolytic; but polarization is not troublesome, because the currents are so small that the polarizing layer takes an almost infinite time to form and disappears by diffusion as it forms. Of these may be mentioned—

Glasses of various compositions.§

Electrolytes in organic solvents. A mixture of 10 per cent alcohol and 90 per cent benzene or toluene has been used widely, but improvements have been made recently.||

* See G. W. Stewart, *Phys. Rev.*, xxvi, 302 (1908); H. E. Ives, *Astrophys. Journ.*, xxxix, 428 (1914).

† See J. G. Frayne, *Phys. Rev.*, xvii, 415 (1921); platinized amber is mentioned by Rosenberg, *Zeits. f. Phys.*, vii, 23 (1921).

‡ See H. E. Ives and A. L. Johnsrud, *Astrophys. Journ.*, lxii, 309 (1925).

§ See C. E. S. Phillips, *Proc. Roy. Soc. Edin.*, xxviii, 627 (1908); V. Andrews, etc., *Proc. Roy. Soc., A*, 117, 649 (1928).

|| See N. R. Campbell, *Phil. Mag.*, xxiii, 668 (1912); G. K. Rollefson, *Science*, ix, 226 (1924); A. Gyomant, *Wiss. Veroff. d. Siemens Konzern*, vi (2), 58 (1928), and vii (1), 134 (1928).

The third class contains only one member, namely, the device that forms one arm of the Maxwellian bridge for measuring capacity. It consists of a condenser C rapidly charged and discharged with frequency n , and having, therefore, a conductance nC .*

All these resistances obey Ohm's Law over a wide range. When the variations of the current are small or when accuracy is not essential, gaseous conductors that do not obey Ohm's Law can be used. Of these the chief are—

Bronson conductors consisting of parallel plates separated by a gas ionized by a radioactive source; and†

Koch conductors consisting of an illuminated photoelectric cell. The characteristic of any photoelectric cell for the first few volts is approximately straight; the approximation is, of course, better the less rapidly saturation is attained, and the spherical cell is better for this purpose than the plane (see Fig. 11). The presence of gas makes saturation slower and extends the range; the voltage must, of course, never be so great that considerable ionization by collision occurs.‡

For some purposes this last conductor has great advantages in principle. Its value can be very easily varied by means of the incident light; and if the same lamp is used to illuminate the conductor and the measuring photoelectric cell in series with it, the steady deflection is approximately independent of variations in the lamp. But for other purposes, the failure of Ohm's Law and the variation with the illumination are disadvantages. Moreover, variable surface charges on the glass introduce troubles when high precision is sought. If we exclude also the very beautiful device of the third class on the score of elaboration, platinized fibres are the best, or, for very high values, the Bronson resistance. But the fibres are difficult to prepare and adjust. The easiest resistances to make and adjust are the electrolytes; their disadvantage is a high temperature coefficient which, however, can apparently be reduced by suitable choice of solute (see Gyemant loc. cit.). Some workers have used the carbon resistances (especially the Indian ink form) with great

* See J. J. Dowling, *Proc. Roy. Dublin Soc.*, xv, 29 (1916).

† See for the latest form R. Jaeger, *Zeit. f. Phys.*, lii, 627 (1928).

‡ See P. P. Koch, *Ann. der. Phys.*, xxxix, 705 (1912).

success; but others—including ourselves—have never succeeded in getting quite the right conditions.

Summary.

Finally, since so many electrostatic methods have been discussed, it may be well to suggest very briefly which of them is preferable to meet various requirements.

Absolute sensitivity in dealing with very small lights.

Direct reading method using a gasfilled cell at maximum magnification, and a Compton or Hoffman electrometer.

Relative sensitivity in detecting very small differences in light.

If compensation from the same source is possible, the null method of page 104 with a vacuum cell and quick reading electrometer, i.e. fibre or Lindemann. If it is not possible, then the constant time method with automatic registration on a quick reading electrometer.*

Absolute precision in measuring the current in amperes.

Null method with compensation by induction (page 114).

Ability to follow rapid changes.

Steady deflection method with quick reading electrometer.

Ease of recording.

Steady deflection with Compton electrometer.

Simplicity of apparatus.

Ticking electrometer.

Methods not mentioned in this list may, of course, be useful when some compromise has to be made between these requirements.

* This method has been employed with great elaboration by C. Muller, *Zeits. f. Phys.*, xxxiv, 824 (1925); *Phys. Zeit.*, xxvi, 932 (1925); *Zeits. fur. tech. Phys.*, ix, 154 and 445 (1928).

CHAPTER XI

VALVE AMPLIFICATION

Electromagnetic Methods.

ELECTROMAGNETIC methods in which the current is measured without previous amplification can be dismissed briefly, not because they are unimportant, but because they are familiar. No reader of this book will need to be told how to use a

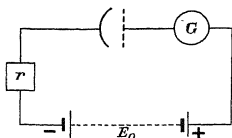


FIG. 31. MEASUREMENT OF CURRENT WITHOUT AMPLIFICATION

galvanometer or ammeter; but for completeness the appropriate circuit is shown in Fig. 31; the only feature requiring notice is the protective resistance. When the current is large enough, this simple method of measurement is the best of all; it is regular and accurate; the same current

always gives the same reading; the relation between reading and current is nearly linear and easily established by calibration. There is practically no voltage drop in the instrument and, consequently, no variation of the voltage across the cell with the illumination. Consequently, there is usually little advantage to be derived from null methods; but if they are required, any of those mentioned in Chapter IX can be used.

The only disadvantage of direct electromagnetic measurement is its lack of sensitivity. Galvanometers with a sensitivity limit for current as low as 10^{-12} amp. are possible (a further reduction of the limit, it may be noted, is theoretically impossible); but when the limit is reduced below 10^{-9} amp., they begin to lose their advantages and to become troublesome, chiefly on account of the instability of the zero. If anything more sensitive than the best type of moving-coil reflecting galvanometer is required, it is probably best to adopt some other method; the limit of such instruments lies between 10^{-9} and 10^{-10} amp. Robust portable instruments can be obtained having a limit of about

10^{-7} amp., and then come the ordinary types of microammeter and milliammeter. Relays can be obtained that are operated by currents of a few microamperes, but they will not stand rough usage; the most sensitive relays that can be recommended for most of the purposes for which relays are required are those used in telephone work, operating with about 5 mA. This figure is important because it defines the limits of valve amplification, which we are about to consider. For many purposes, and especially for detection associated with control, which is here such an important field, amplification by valves beyond 10 mA. is unnecessary, because any further amplification is better effected by means of mechanical relays.

Principles of Valve Amplification.

When electromagnetic methods are to be used, and the current given directly by the cell is insufficient for the purpose, it must be amplified. To-day, such amplification is always by thermionic valves; indeed, it is the development of the thermionic valve that has brought the photoelectric cell into prominence and led to most of its modern applications. The essentials of any circuit for such amplification are shown in Fig. 32, which may be regarded as a modification of Fig. 25, produced by substituting the grid of a valve for the leaf of an electrometer; an electromagnetic instrument is placed in the anode circuit. But one small difference between Fig. 32 and Fig. 25 requires passing mention, namely, that while the anode of the cell is shown connected to the electrometer in Fig. 25, the cathode is shown connected to the grid in Fig. 32. When an electrometer is used, it is immaterial in principle which electrode is connected to it; but it is usually convenient to choose the anode because it is better insulated. When a valve is used, it is usually convenient to choose the cathode, because the high-tension battery which supplies the anode circuit can also supply the cell, as shown; but we shall see that the choice is no longer immaterial in principle, and that in some circumstances the connections of the cell must be reversed and a separate source of potential used.

There are two main differences between the use of valves to replace an electrometer and their use for more familiar

purposes, such as radio reception. The first, expressed briefly, is that the currents to be amplified are often direct and not alternating. However, the distinction between a variable direct current and an alternating current is one of degree rather than of kind; the difference is better expressed if we say that the electrical changes to be amplified are too slow to be transmitted through transformers or condensers, and so slow that, during their occurrence, the state of the amplifying system may alter appreciably. The effect of such alterations will concern us presently; but the impossibility

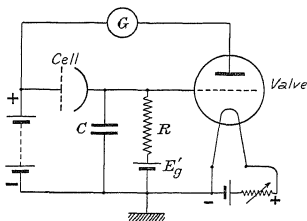


FIG. 32. VALVE AMPLIFICATION

of using the normal form of coupling influences design from the first. The cell and the valve must be connected conductively. Further, the condenser C , representing the capacity of the cell and its connections, can be left out of account; any method in which it exerted an influence should be classified as alternating current amplification; in all the methods of this chapter, sufficient time must be allowed for the system to reach a steady state.

The second difference is that we are concerned with current rather than with voltage magnification. The current in the grid circuit is what we want to measure; the current in the anode circuit is what we shall observe; moreover, the impedance of the part of the anode circuit exterior to the valve will always be negligibly small. The useful magnification will be the ratio of the change of anode current i_a , when there is no external impedance, to the change of i , the current through the cell; this ratio will be called A .

Perhaps a clear understanding of the principles involved in the adjustment of the circuit is best attained by supposing first that the resistance R is infinite, so that the cathode of the cell and the grid form an insulated system. If the cell is dark and this system starts at a potential positive to the filament, it will receive some electrons from the filament, though most of them go to the anode; it will acquire a negative charge, which will tend to prevent more electrons reaching it; finally it will attain a potential, usually a little negative to the filament, at which it receives no more electrons. If light now falls on the cell, electrons can leave the grid by way of the cathode of the cell; the grid potential will rise, until the electrons received from the filament balance those lost through the cell. In other words, i_g , the grid current, will be equal to i , and we shall have

$$A = di_a/di = di_a/di_g \quad . \quad . \quad . \quad (27)$$

A is then a property of the valve, which might be determined by plotting i_a against i_g and taking the slope of the curve. However, since it is usual to plot valve characteristics with the grid potential E_g as base, it may be more convenient to write (27)

$$A = di_a/di_g = \frac{di_a}{dE_g} \bigg/ \frac{di_g}{dE_g} = M/\Gamma_g \quad . \quad . \quad (28)$$

where

$$M = di_a/dE_g$$

is usually called the mutual conductance of the valve, and

$$\Gamma_g = di_g/dE_g$$

may be called the grid conductance.

That this latter term is appropriate appears at once if we make an assumption precisely opposite to that which we have just made. We suppose now that R is finite and consists of a grid leak having a finite conductance $\Gamma = 1/R$, and that the grid current is zero. i flowing through R will produce a potential $E_g = i/\Gamma$ between grid and filament, and A is clearly given by

$$A = \frac{di_a}{dE_g} \bigg/ \frac{di}{dE_g} = M/\Gamma \quad . \quad . \quad . \quad (29)$$

It is easy to see that, if we combine the assumptions, and suppose that there is both a finite grid leak and a grid current

$$A = M / (\Gamma + \Gamma_g) \quad . \quad . \quad . \quad . \quad (30)$$

Valve Characteristics.

Fig. 33 shows the relevant characteristics of a valve suitable for the purposes we are considering; it is an Osram P.625 with an anode potential of 120 volts. In the three curves, i_a , i_g , and Γ_g are plotted against E_g . The (i_a, E_g) curve is nearly straight; M is nearly constant, and the variation of A with E_g will depend on the variation of Γ_g , since Γ is constant.

If $\Gamma = 0$ and there is no grid leak, it will be impossible to apply grid bias, and the value of Γ_g will be that corresponding to $i_g = i$, or, since we are supposed to be dealing with very small photoelectric currents, to $i_g = 0$. But this condition is clearly not the most favourable. For Γ_g is varying very rapidly with E_g and i_g in this neighbourhood, so that the amplification will not be approximately linear for any but very small variations of current; further, Γ_g is greater than it is when E_g is smaller and corresponds to negative values of i . It is better to insert a grid leak of very high resistance and apply a negative grid bias. In fact, by so doing, we can ideally attain infinite amplification. For Γ_g in one region is actually negative (see, further, page 145); if we apply grid bias so that E_g lies in this region, and make $\Gamma = \Gamma_g$, $\Gamma + \Gamma_g = 0$ and $A = \infty$.

Actually, this is impracticable; there are the conductances of the insulation and possibly of the cell itself (see page 115) to be considered; but much more important is the irregularity of the valve which sets a definite limit to the useful amplification. Probably nothing is ever gained by making Γ less than 10^{-8} mhos; and with so large a value Γ_g will be inappreciable unless positive grid bias is applied; the cell conductance will be inappreciable, and, though the insulation leak of some valves may be of this order, it can and should also be made of no account. The conclusion at which we arrive is thus very trite and obvious; it is that which everyone familiar with valves in their normal uses would immediately adopt; but it is as well to have seen the reason for it.

We must pass the photoelectric current through as high a resistance as possible, the limit being reached (as usual) when

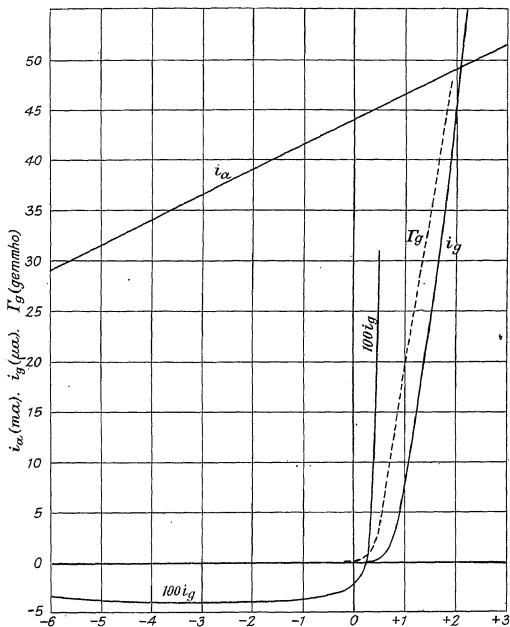


FIG. 33. VALVE CHARACTERISTICS

irregularity makes increase of ideal sensitivity no longer an increase in effective sensitivity; and we must apply a small negative grid bias, the exact value of which will not matter so long as it is not so great as to carry the valve into the

region where the slope of the (i_a, E_a) characteristic falls and M decreases. With the valve to which Fig. 32 refers, M will then be 2.5×10^{-3} ; so that if $\Gamma = 10^{-8}$, $A = 250,000$. Even this is probably an overestimate of the amplification that is actually useful; no one seems to have succeeded in making measurements with any pretence to precision with an amplification greater than 50,000. If the amplification is so great that the regularity limit is much greater than the sensitivity limit, it should be reduced by decreasing R .

But is not the choice of valve or of the anode voltage important? If it were possible to use the greatest amplification of which a valve is capable according to (30), the choice would be very important. M is greatest in valves of the power type, and in valves with a screening grid between the control grid and the anode, and it is somewhat greater with high anode voltages than with low. Γ_a is least with a "space-charge" grid between filament and control grid, which permits the adoption of very low anode voltages.* On such grounds many writers recommend strongly the use of some particular type of valve. But since the limit to amplification is set, not by (30), but by inevitable irregularities, these considerations are irrelevant; amplifications as great as irregularity will permit can be obtained with almost any valve of the normal types with any reasonable anode voltage; and there is no evidence that the irregularities, the source of which we are about to consider, are materially less with one of these types of valve than with another.

However, the possibility of some new type of valve specially designed for the purpose is worth consideration. The only proposal in this direction of which we are aware is to combine photoelectric cell and valve in a single unit enclosed in the same exhausted envelope.† The control electrode may then be the photoelectric cathode, and may have a form very different from that of the ordinary grid. Thus if the filament and anode of the valve are placed at the ends of a tube, of which the walls are coated with a layer of

* G. Ferrié, *Comptes Rendues*, clxxviii, 1117 (1924).

† See, e.g. V. K. Zworykin, U.S. patent 1,677,316 and *Phys. Rev.*, xxv, 247 (1925); J. M. Hyatt, *Phys. Rev.*, xxiii, 501, (1924); T. W. Case, *Journ. Opt. Soc., America*, vi, 639 (1922); V. M. Albers, *Phys. Rev.*, xxvi, 671 (1925). Also British patents 178917, 209818, 224874.

photoelectric metal, the filament-anode current will be influenced by the potential of this layer, and this potential, being determined by the relation between the thermionic electrons arriving at the layer and the photoelectric electrons leaving it, will vary with the light in the same way as the grid of the valve, externally connected to the photoelectric cathode, in the arrangement of Fig. 32. Such a device might tend to produce regularity by reducing to a minimum the opportunity of the insulated grid system to pick up extraneous disturbances, but we know of no evidence that it actually has that advantage. For though patent and other literature is full of proposals of this nature, they do not appear to have been widely used. The main objection to them is, of course, the difficulty of obtaining an efficient photoelectric cathode in such circumstances, and of avoiding the incidence upon it of light from the incandescent cathode; this last difficulty is not so serious when valve filaments are used which give a copious emission at very low temperatures, but then the first difficulty becomes more serious.

Sources of Irregularity.

The sensitivity of valve amplification is then limited by its freedom from irregular disturbances. These arise from three sources. The first is external to the apparatus. The circuit is very sensitive to high frequency disturbance; for it is essentially that of the familiar "grid leak detector" used in radio reception. Few places nowadays are free from such disturbances; even if there are no unintentional transmitters in the neighbourhood, no induction coils or sparking commutators on motors, generators, or regulators, there are always the intentional transmitters. This source can be removed by enclosing the apparatus completely in a conducting shield, preferably earthed; but the enclosure must be complete, and, in the last resort, must contain the whole apparatus, including the batteries and the source of light. Some experimenters, finding practically no benefit from partial enclosure or from placing large condensers across all leads, have rashly concluded that the irregularities that troubled them were not of external origin. But in the matter of shielding, it is the last step that counts; the final sealing of some crack that looks too small to be noticed,

or the substitution of a soldered for a less perfect connection, will often make the whole difference between success and failure. Of course, in favoured localities or where the utmost sensitivity is not required, less complete shielding or even no shielding at all can be tolerated; but irregularities should be sought in other directions only when the most complete shielding that can be devised fails to eliminate them. Perfect shielding is attainable; our colleagues, working in a building drenched with high frequency disturbances of every description, have found it possible to obtain perfect regularity even with amplifications of the order of 50,000.

The second source of irregularity lies in the batteries. It must be remembered that changes in the potential between grid and filament will be amplified in the same way, whether they are caused by a current from the photoelectric cell or by a change in the voltage of the batteries. The constancy of the grid bias battery is, of course, most important, but that of the filament battery scarcely less so; changes in the latter produce changes in the effective grid voltage, partly because this depends somewhat on the velocity of emission of the thermionic electrons, which depends on the temperature, but more because the cathode (unless indirectly heated) is not all at the same voltage, but covers the whole range of the voltage applied to it. Variations of the anode voltage are somewhat less important, for these are reduced effectively by the magnification factor of the valve.

Slow regular variations of the voltages as the batteries run down are unavoidable, but they are usually of little importance; trouble will arise only from rapid and irregular changes. From their accounts, some experimenters seem to have been very unfortunate in this matter; but we have never traced any material irregularities to properly maintained accumulators or dry cells used for the anode and grid battery.

The third source of irregularity is the thermionic emission of the valve filament. This emission is affected by minute changes in the surface, similar to those that affect so greatly photoelectric emission. There is always some residual gas in a valve, absorbed or free; any alteration of the electric field or of the temperature may shift some of this gas to or from the surface of the filament, and change the emission

of the whole or of one part relative to another, and thereby change the relation between anode current and grid potential or grid current. The anode current is determined by past as well as present conditions, and when the amplifier is first put into action or started again after a rest, it will change continuously for a period of many hours. It is probable that in this matter the pure tungsten filaments of the old "bright emitter" valves are preferable to any form of "dull emitter"; and if the amplifier cannot be left undisturbed until it has settled down, such filaments should be used. If the filament battery has to be recharged or any other alteration made, it is important to make switching off the filament the first operation, and switching it on the last; above all, the filament should never be switched on without the anode voltage and, approximately, the right grid voltage. But the best plan is to avoid alterations as far as possible; and, when they must be made, to make them (e.g.) overnight, so that the apparatus has time to attain a steady state before it is used next day.

In principle, irregularities from this source should be reduced if the amplification were divided between several stages, and only a relatively small amplification attempted in each stage. In the later stages the arrangement of Fig. 32 is repeated, the current in the anode circuit of each stage being treated in the same way as the photoelectric current from the cell. But the difficulties of multi-stage, direct-current amplification are so great, owing to the need for insulated batteries or their equivalent, that success in this direction is unlikely.

As a matter of interest, not of practical importance, it may be mentioned that the theoretical limit to the sensitivity attainable by amplification arises from an essential irregularity in all thermionic emission. The temperature of the filament and the nature of its surface determine the average rate of the emission of electrons, but the individual emissions are determined by chance; the electrons emerge like bullets from a squad at independent firing, not like those from a machine gun. But though the fundamental irregularity due to this cause has been detected and measured, it is probably always masked by other irregularities in the conditions relevant to our problem.

Finally, it may be observed that freedom from quick irregularities (and slow changes are not of much importance) can always be promoted by using a very sluggish instrument in the anode circuit. When very high amplifications have been attained, such instruments have usually been employed. But this is not a satisfactory solution of the difficulty; for speed should be one of the main merits of valve amplification as compared with electrometer methods.

Bridge Amplifier.

But even when all sources of irregularity are eliminated by careful design of the apparatus, and by adjustment of the sensitivity by a suitable choice of grid leak, the simple circuit of Fig. 32 is not convenient for comparison and measurement, because the current in the anode circuit does not fall to zero with the photoelectric current. When the comparison of two illuminations thrown alternately on the same cell is required, the commutation methods of page 105 may be employed, exactly as if the anode current proceeded directly from the cell. But even in this case, and still more in all others, compensation of the anode current corresponding to $i = 0$ is desirable. By far the best plan is to use the bridge circuit shown in Fig. 34, for it helps to eliminate some of the sources of irregularity.

Here the anode current from the valve amplifying the photoelectric current is compensated by the anode current from a similar valve, the grid of which is maintained at a fixed potential. There is necessarily some loss of ideal sensitivity which should be more than balanced by gain of regularity. If the circuit is regarded as a Wheatstone bridge, and the usual formula is used for the change in I_G , the current through the indicating instrument G , due to introducing a small E.M.F. into one arm of the balanced bridge, it is easily deduced that the sensitivity is reduced in the ratio $1/S$, where

$$S = 2 + \frac{R_g}{X} \left(1 + \frac{X}{r_1} \right) \quad . \quad . \quad . \quad . \quad (31)$$

R_g is the resistance of G , X the impedance of each valve (according to the usual definition). That is to say, the change of anode current due to a given i when one of the

valves is used separately is S times the value of I_G corresponding to the same i when the bridge is used. Now X will be of the order of 10,000 ohms, and large compared with R_g ; consequently, so long as r_1 is not very small compared with X , S will differ little from 2. The lower limit placed on r_1 and r_2 is thus that they shall not be much less than 10,000 ohms; a higher limit is set by the condition

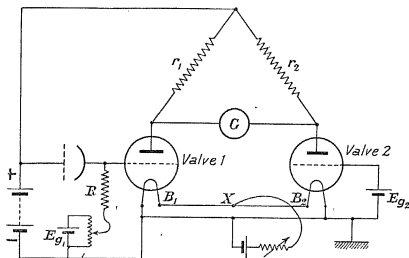


FIG. 34. BRIDGE AMPLIFIER

that the potential drop ri_a in the resistances shall not be inconveniently large.

If all the characteristics of the two valves were exactly the same, it would be possible to obtain perfect independence of changes of anode and filament battery voltage, when $i = 0$, by making the two sides of the bridge exactly symmetrical. But, actually, the characteristics are never exactly the same, and complete symmetry is impossible; either r_1, r_2 must be different or E_{g1} and E_{g2} , and since some asymmetry is unavoidable, it is not worth while to insert a resistance R in the grid circuit of valve 2, though it would be necessary for complete symmetry. Perfect independence of the battery voltages is lost, but partial independence remains and can be increased by empirical adjustment. If the ratio r_1/r_2 is changed, while a balance is maintained by varying E_{g2} , a value for the ratio can usually be found such that the balance is not changed by a small change made intentionally in the anode voltage; if it cannot be found, or

if the value found is very different from 1, the valves are too dissimilar and another pair should be tried. Similarly, independence of the filament battery voltage can be attained by making B_1B_2 a resistance of about one-tenth of the filament resistance—a straight resistance wire is convenient—and moving the slider X along it until a small change in the battery voltage leaves the balance unchanged. These two adjustments are not wholly independent, and they must be repeated alternately until they are both perfect.*

In our experience, as has been indicated already, these adjustments are not really necessary if suitable batteries are employed; the most they can do is to eliminate a very slow regular drift of the zero, which is usually of little importance. Quick irregular variations, which are much more serious, do not generally arise in the batteries.

Use of Valve Amplification.

The amplifier that we have been discussing is a substitute for an electrometer; its method of use and range of usefulness are similar; and many of the conclusions about sensitivity and accuracy can be transferred with little alteration, especially those concerned with vacuum and gas-filled cells. Direct-reading measurement is possible if a sufficiently stable zero can be obtained, and if the limits within which amplification is linear are not transgressed; i is taken as proportional to I_G . But, generally, null methods are preferable, just as they are with electrometers. Compensation by a second photoelectric cell is always possible, and has the same advantage as with other methods of comparison; the induction method is not suitable. The balance can also be adjusted by varying the grid potential E_{g2} of the compensating valve, and for small changes the current can be taken as proportional to the change in E_{g2} . But a far more satisfactory method is to compensate by means of E_{g1} , thus using the ohmic resistance method of page 103. For the change in the current through R necessary to restore the balance when the light is changed is exactly equal to the change in i produced by the light, and is independent of the valve characteristics. If R and the potentiometer applying E_{g1} (see Fig. 34) are once calibrated in terms of illumination, the calibration will

* C. E. Wynn-Williams, *Proc. Cam. Phil. Soc.*, xxiii, 811 (1927).

be unaltered so long as the same cell is used, even if the valves are changed. Moreover, the voltage across the cell when the balance is made and the reading taken is always the same; complications owing to lack of saturation do not arise.

It is desirable in this method that the bridge should be balanced when $i_g = 0$; and that, since E_{go} , the corresponding grid potential, is not in general zero, a permanent grid bias E_{go} should be inserted in series with the potentiometer and independent of it. For then the potentiometer will read zero when $i = 0$, and, if R is changed, the calibration of the scale of the potentiometer in terms of photoelectric current will be altered throughout by a constant factor; if E_p is the potentiometer potential at balance, $i = E_p/R$ whatever the value of R . The possibility of changing R enables a very wide range of illumination to be measured without the use of any high potentials on the potentiometer. It may be observed incidentally that an easy way to test whether the permanent grid bias is indeed E_{go} is to shunt the grid leak R when $i = 0$, and the potentiometer is at zero; if the adjustment is correct, the balance will not be disturbed; but in making this test, precautions must be taken against thermoelectric or voltaic E.M.F.'s. introduced by the shunt. There is some loss of ideal sensitivity involved in working at $i_g = 0$ instead of nearer the point where $I_g = 0$, but, as we have insisted, not of effective sensitivity.

It remains to compare valve and electrometer methods. Calculations have often been published purporting to show that the sensitivity attainable by valve amplification exceeds greatly anything that has ever been reached by an electrometer of normal design; but the sensitivity concerned in these calculations is the ideal sensitivity that takes no account of regularity. Our own experiments indicate that they are wholly misleading, and that the effective sensitivity of electrometer methods is decidedly greater. Alone they would not be conclusive, for we have worked in a building subject to intense high frequency disturbances and unfavourable to the use of valves; but we learn from many sources that others who have made careful comparisons have been forced, often unwillingly, to the same conclusion. If the measurement of very small currents is the problem in

view, we have no hesitation in recommending the electrometer except, possibly, in the measurement of absorption (see page 191). Even for larger currents, we think that the electrometer is more suitable in laboratory experiments, where ready adaptability is essential and cumbersome apparatus a nuisance. But valve amplification has a very useful field when long series of measurements have to be made, especially by relatively unskilled operators; it is then worth while to spend much time and labour in erecting a complicated piece of apparatus, if only it will be simple to handle and unlikely to get out of adjustment when complete. The comparatively insensitive electromagnetic instrument that can be used as G in the valve amplifier is much easier to read than any electrometer, and, unlike the electrometer, it can easily be placed at any convenient distance from the cell; it is suitable for lecture demonstrations and similar purposes.

Detection and Control.

On the other hand, there is one field in which the electrometer cannot enter into competition at all; namely, where control is required and the minute currents and energies characteristic of electrometer methods are utterly insufficient to work the subsidiary mechanism. If nothing more than detection is required and delicate quantitative distinctions are unimportant, features of the valve characteristic that we have left out of account so far, and that are disadvantageous in quantitative work, can be turned to positive advantage.

If the simple theory expounded on page 133 were complete, i_g could never be less than zero, however negative E_g becomes. But, actually, as Fig. 33 shows, i_g decreases beyond zero with decreasing E_g , attains a minimum (or negative maximum) and then rises slowly to zero again. In order to show this, part of the i_g curve, marked 100 i_g , is plotted on a larger scale. The negative grid current, or "backlash," that appears when E_g is less than E_{g0} , is due to the presence of positive ions produced by collision of the thermionic electrons with the residual gas that is present in the most perfectly evacuated valve. In the old soft valves, familiar to wireless pioneers, it was large and

important, determining largely the behaviour of the valve in its ordinary uses; in modern hard valves it is quite unimportant except in special uses such as we are considering now. The positive ions are attracted to the grid when it becomes negative and ceases to receive electrons; the maximum backlash i'_g is reached when the greatest number of ions and the smallest number of electrons are received. When E_g is made still more negative, the backlash decreases because the anode current, by which the ions are produced, decreases; when the anode current is stopped altogether the backlash is zero, and any remaining i_g is due to insulation leak.

If the cell is connected to the valve in the manner shown in Fig. 32, the backlash is unimportant; for, if there is no grid leak, i_g can never be less than 0, since electrons never flow to the grid from the cell; if there is a grid leak, its conductance is always greater than I_g in the region of maximum backlash, for here I_g is zero. But if the cell is turned the other way round and its anode connected to the grid (the cell battery being reversed, of course, at the same time), and if there is no grid leak, the backlash becomes very important. For electrons from the cell will be forced into the grid by the cell battery, and will carry E_g towards the point of maximum backlash. If the photoelectric current is greater than i_g (which is generally of the order of 10^{-8} amp.), the excess cannot escape from the grid at all; electrons cannot leave the grid, and the positive ions are insufficient for their neutralization. Accordingly, E_g will fall till it becomes equal to the cell battery potential and the photoelectric current ceases; if the battery potential is sufficient (more than 30 volts) the anode current will be completely stopped.

✓ Here we have an extraordinarily powerful method of detection. It is also extremely simple when the circuit can be fed from mains giving a potential E_o of 200 volts or more, and there is no objection to wasting the power required to heat the filament of the valve directly from the mains (Fig. 35.) The resistances r_+ and r_- are chosen so that $E_o/(r_+ + r_-)$ is equal to the filament current (the resistance of the filament can usually be neglected), and so that $E_o r_+$ is equal to the appropriate anode voltage; $E_o r_-$ will then be the voltage applied to the cell, and will be great enough, when applied to the grid, to reduce i_a to zero. When no light falls on the

cell, i_a will assume the value corresponding to $i_g = 0$; with a "power valve" this will be more than 10 mA; i_g will be about 10^{-8} amp., and any illumination giving an i greater than this will reduce i_a to zero. The effective current amplification will thus be of the order of one million. The same circuit can, of course, be used with independent supplies to the valve filament, valve anode, and cell cathode.

The same circuit may be used even if the supply from the mains is alternating current, not direct current. For when the direction of the supply voltage is opposite to that

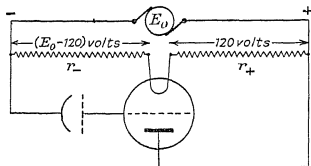


FIG. 35. AMPLIFYING CIRCUIT FOR USE OFF SUPPLY MAINS

shown in Fig. 35, the valve will pass no current since the anode is negative. The cell may pass a small positive charge to the grid, because the anode has usually some photoelectric emission; but if this emission is very much smaller than that of the cathode (as it usually is), the positive charge received by the grid in this phase will not be enough to neutralize the negative charge received during the opposite phase; when the anode of the valve becomes positive once more, the grid will still be negative. On the other hand, during the change of the valve anode from positive to negative, a positive charge will be induced on the grid; but the resulting rise of potential may be abolished by connecting a condenser of about $0.0005 \mu\text{F.}$ between the grid and earth. With this addition, the circuit will operate as before and pass current only when the cell is dark; but this current will be smaller, because the anode is positive for only half of the period, and the response will be rather slower, because a larger capacity has to be charged or discharged when the change between light and darkness occurs. It is not strictly

necessary now that the cell cathode and valve anode should be connected to points on the resistance on opposite sides of the valve filament; but, of course, the potential across the cell must never be allowed to rise to the glow potential.

Similar results can be obtained by substituting for the thermionic triode a gas-discharge triode, consisting of any form of discharge tube (e.g. a neon lamp or a mercury rectifier) in which a third electrode or grid is placed in a suitable position near the anode. In such a tube, the potential at which the discharge starts is reduced considerably if a small current is allowed to flow from the anode to the grid.* If the voltage applied to the main electrodes lies between the starting potentials with and without this current, the discharge can be made to start by throwing light on a photoelectric cell connected between the anode and grid. Many amperes in the main circuit can thus be started by a fraction of a microampere in the cell; but the arrangement has the disadvantage that the current does not stop when the light is turned off; for the potential of the grid necessary to start the discharge is maintained by the discharge itself. If the supply is alternating current of ordinary frequency, the interval between voltage peaks is still too small to allow the charge on the grid to leak away; the discharge will not stop unless the voltage is so adjusted that the current produced by the light is relatively small. Nevertheless, the grid-discharge tube may be very useful if the function of the cell is only to give an alarm, and the continuance of the effect after the cause has ceased is not undesirable.

Even when the thermionic amplifier is used, there is some instability of this kind. The photoelectric current necessary to suppress the anode current is less than that required to maintain the suppression, because the backlash vanishes with the anode current; if i is raised until i_a just falls to zero and then decreased slightly, i_a will not rise. In fact, if i_a were reduced completely to zero, and if the charge on the grid did not leak away through the insulation, i_a would remain zero even when i was reduced to zero.

For this reason the circuit is entirely unsuited to any

* T. R. Wilkins, *Journ. Opt. Soc., America*, xvi, 370 (1928). Thermionic valves having the same characteristic are discussed, under the name of "Thyratrons," by A. W. Hull, *Gen. Elec. Review*, xxxii, 213 (1929).

quantitative measurement or even comparison. Further, since the critical illumination that reduces i_a to zero is determined by the backlash, which cannot be trusted to remain constant for long periods, it is not suitable even for detection, if accuracy is required. These objections can be removed by using a second photoelectric cell under constant illumination with its cathode joined to the grid to provide an artificial backlash large compared with the real backlash. In fact, the arrangement is then a balance essentially similar to that of Fig. 24, and might be used for comparison in the same way. A larger current from the first cell is then necessary to stop the anode current, and there is, therefore, some loss of sensitivity in detection; but for many purposes the sensitivity is still sufficient.

“Time-Lag.”

We started by saying that the photoelectric current to be amplified was always direct and not alternating; but in some of the most important applications of cells this statement is not true, because the light incident on the cell is fluctuating. When the light is fluctuating with a frequency of 50 to 10,000 cycles per second, the problem of amplifying the resulting current is essentially similar to that of audio-frequency amplification in radio reception. Frequencies much greater than 10,000 need hardly be considered, for they do not arise in any application that has been made so far. But a preliminary question arises. Will the photoelectric current follow faithfully such rapid variations of the light; or is there some inertia or “time-lag” in its action.

The answer is that there is no inertia or delay in the photoelectric emission itself. If there is any interval between the incidence of the light and the emergence of the full quota of electrons corresponding to that light, it is certainly less than 10^{-3} seconds, and beyond the range of any measurement.* There is nothing similar to the gradual development of the full effect of the light which is characteristic of the selenium cell. Nor is an appreciable time required for the full quota of emergent electrons to reach the anode in any vacuum cell, even the largest; moreover, even if it were appreciable, it would be immaterial; for, if the

* See E. O. Lawrence and J. W. Beams, *Phys. Rev.*, xxix, 903 (1927).

voltage applied to the cell were constant, it would cause merely a slight delay in the response, but no diminution or distortion of it.

On the other hand, distortion may enter in the apparatus for measuring the electronic current. The cell and the apparatus to which it is connected always have a finite capacity, and a current i , from whatever source it is derived, cannot charge a capacity C to a potential E more than i/CE times per second. The effect of this limitation upon the measurement of light varying with a high frequency is easily

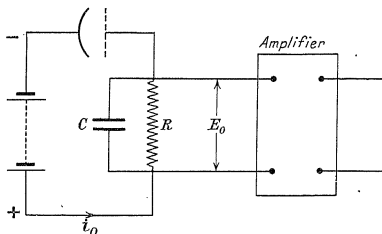


FIG. 36. RESISTANCE-COUPLED AMPLIFIER

calculated. The essential elements of all circuits used in the amplification by valves of alternating currents are shown in Fig. 36. An alternating current of amplitude i_o and frequency n produces an alternating voltage of amplitude E_o across the condenser C and resistance R which is applied to the valve; the sensitivity of the circuit will be measured by E_o/i_o ; if there is to be no loss of sensitivity at the higher frequencies, and no distortion of a disturbance covering a range of frequencies, this ratio must be independent of n . Actually, we have

$$E_o/i_o = R/\sqrt{1 + 4\pi^2 n^2 C^2 R^2} \quad (32)$$

The condition for no distortion is that $2\pi nCR$ should be small compared with 1; the condition for sensitivity is that R should be great. These two conditions are contrary; for n is fixed, and C , which includes the capacity of the cell itself, cannot be reduced indefinitely; in the last resort, distortion

can be abolished only by sacrificing sensitivity. Thus if C cannot be reduced below $20\mu\mu\text{F}$.—and in practice it will be above rather than below this value—some distortion will enter at 1,000 cycles unless R is small compared with 10 megohms, and at 10,000 cycles unless it is small compared with 1 megohm. Accordingly, at 10,000 cycles, a photoelectric current with an amplitude of one microampere must not be allowed to produce an amplitude comparable with 1 volt on the grid of the valve. This condition can usually be relaxed somewhat, because E_o/i_o can often be allowed to vary considerably with the voltage before the distortion becomes appreciable in the reproduction of sounds or of light and shade in a picture; but an amplitude much greater than 1 volt would certainly cause trouble.

If additional sensitivity is sought by the use of gas-filled cells, distortion might enter at large magnifications. The process described on page 55, whereby ionization by collision magnifies the primary currents, takes a finite time. If the magnification is small, and the positive ions do not generate an appreciable number of secondary electrons at the cathode, the time will be no more than is required for ions generated near the anode to reach the cathode. The ions move more slowly than the electrons, and the time will, therefore, be greater than that required for the electrons to reach the anode in a vacuum cell; but it will still be less than 10^{-6} seconds, and should not affect matters at the frequencies that are relevant here. Moreover, it would be a mere delay and should not produce distortion. If the magnification is greater, and the positive ions produce an appreciable number of electrons, the delay will be longer; for the secondaries have to travel across, and then the tertiaries, and so on, until a steady state is established. Moreover, the delay might now produce distortion, for the ultimate steady state will depend on the rate at which electrons are being liberated from the cathode at all times from the first incidence of the light to the establishment of the steady state; rapidly succeeding variations will interfere with each other.

The frequencies at which such distortion should appear cannot be calculated with any precision, because enough is not known about the details of the process. But rough estimates of orders of magnitudes do not suggest that it

should be appreciable at frequencies as low as 10,000. Further, the glow discharge in a neon tube arises from ionization by collision; it involves the establishment of a similar steady state in vessels of about the same volume as a photoelectric cell by electric fields of about the same magnitude; this discharge is known to follow alternations of voltage as rapid as 30,000 per second, ceasing when the voltage drops and starting again when it rises. If, therefore, any distortion occurs in the reproduction by a gas-filled photoelectric cell of light varying with audio-frequency, it must be due to some feature of the process neglected by the simple theory that has been outlined.

In actual fact, it seems that serious distortion may occur at frequencies as low as 2,000, over and above that due to the capacity according to (32). We have not investigated the matter ourselves, nor have we discovered any detailed account of an investigation by others. But incidental references in accounts of picture telegraphy and talking films indicate clearly that, in the conditions that commonly prevail, the ratio E_o/i_o in (32), falls off very rapidly at the higher audio-frequencies. Some systems combat this diminution by elaborate compensating circuits, usually inserted in the later stages of the amplifier, consisting of impedances increasing with the frequency as the current supplied to them decreases. We can suggest no explanation; further inquiry is urgently needed, especially to determine whether the diminution of response with increasing frequency depends at all upon the type of gas-filled cell or upon the nature and pressure of the gas-filling; in any comparison of this nature the magnification must always be the same, for the trouble seems to be entirely absent in vacuum cells, and doubtless increases rapidly with the magnification.

Alternating-current Valve Circuit.

When the photoelectric currents are alternating, conductive coupling between the cell and valve can be replaced by any of the couplings used in radio reception. Resistance-capacity coupling is usually adopted so that the first two stages are arranged as shown in Fig. 37; in the later stages modifications are often introduced.

It should be observed that the capacity C in (32) is not

that of the coupling condenser C_o . If, as is usual, C_o is large compared with C_1 and C_2 , the capacities to earth of the cell electrode and of the grid of the first valve, C is rather the sum of these capacities. R is then roughly the resistance of R_1 and R_2 in parallel. These resistances are of the order of 1 megohm. Since appreciable distortion will enter, according to (32), when the frequency is of the order of 10,000, if $(C_1 + C_2)$ rises above $30 \mu\mu\text{F.}$, it is important that it should be kept as low as possible; for this purpose it is necessary to keep the cell and the first valve close together,

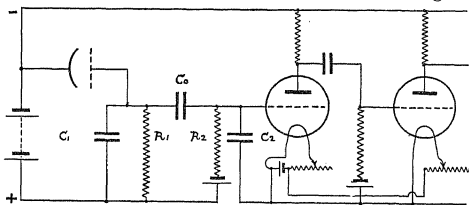


FIG. 37. AMPLIFICATION OF RAPIDLY VARYING PHOTOELECTRIC CURRENTS

in order that the capacity of the leads from one to the other shall not be large. It is immaterial for the action of the circuit whether the anode or the cathode of the cell is connected to the valve, nor can the choice affect that part of the capacity which arises from the interaction of these two electrodes. But it may affect the capacity to earth; the capacity to earth of the anode is usually less than that of the cathode.

Volumes might be, and indeed have been, written on the elaboration of this circuit, and on the subsidiary devices that are necessary when the alternating photoelectric currents are drawn from an apparatus for picture telegraphy, television, or talking films.* If we dismiss them here unnoticed, it is not because we fail to realize their importance; the use of photoelectric cells for these purposes is the

* The most complete description of the electrical side of a television system is probably that given in the series of papers published in the *Bell System Technical Journal*, vi, 551-562 (1927).

immediate cause of the interest they have aroused lately, and therefore for the compilation of this book. It is rather because we are unwilling to enter at all into a region which the limits of our space and of our knowledge would forbid as to explore completely.

Generation of Alternating Current.

When the light to be measured or detected is not naturally alternating with a suitable frequency, it may be desirable to introduce some device to make the photoelectric currents alternating, in order that advantage may be taken of the superiority of alternating-current over direct-current amplification.

One method is to introduce into the path of the light an interrupting shutter, usually consisting of a rotating disc pierced with holes. A disc with 10 holes mounted on the shaft of a motor making 1,800 revs. per minute, gives a frequency of 300 cycles, which is easily amplified. It should be observed that this method involves the loss of half the light.

When the problem is one of the comparison of two illuminations, they may be thrown alternately on the same cell by an arrangement of mirrors or shutters working at a suitable frequency. When the two illuminations are equal, the alternating component of the photoelectric current, which may be selected by passing the current through a transformer, will vanish. The position of balance can be determined by a minimum of sound in a telephone; or the amplified alternating-current component may be rectified and read on a galvanometer; or, again, it can be amplified still further and made to control some mechanism which adjusts the light balance so that the alternating component vanishes, and thus enables measurements to be made and recorded automatically. Proposals for both the simple and the more complex modifications of this method have often been made and preliminary apparatus constructed; but we believe that hitherto some alternative method has always been adopted ultimately.* Doubtless, one of the difficulties

* This statement has ceased to be true. A very elegant apparatus for the spectrophotometric determination of colour, using this method, has been described by A. C. Hardy, *Journ. Opt. Soc., America*, xviii, 96 (1929). This paper is valuable for the full description of the methods of valve amplification employed.

is to secure that the alternating component really vanishes when the illuminations are equal; for this will be achieved only if the optical arrangements are very carefully designed, so that the decrease of the illumination from one source occurs at exactly the same rate as the increase of the illumination from the other; the sum of the two illuminations must remain strictly constant when the balance is reached. If this difficulty could be overcome completely, the method would doubtless have great advantages.

Another possible method is to apply an alternating voltage to the cell. Since the full voltage in the right direction would then be applied for only a small fraction of the cycle, the loss of sensitivity would be enormous if gas-filled cells were used and very considerable even in vacuum cells. Moreover, in addition to the photoelectric current, there would be a spurious current arising from the charging and discharging of the capacity of the cell, which would become very prominent at the higher frequencies. When this method is proposed it is always in conjunction with a three-electrode cell, in which a relatively small alternating voltage is applied between the cathode and a grid interposed between the cathode and anode; according as this grid is positive or negative to the cathode, the electrons are permitted or denied access to the anode region in which they may produce ionization as in any other gas-filled cell.* If such photoelectric triodes are to be satisfactory, there must be little or no emission from the grid; the grid must be prevented from acquiring a surface film of photoelectric material (see page 6). Perhaps for this reason, or perhaps for some other, photoelectric triodes are not employed in any apparatus of which we have seen a description.

Lastly, the constant or slowly varying photoelectric current may be passed through a commutator or interrupter before it is passed to the amplifier. This method appears at first sight rather heroic, and great difficulties might be anticipated in constructing a mechanical device suitable for commutating such very small currents at high frequencies. Nevertheless, it has been used successfully when circumstances make other methods very difficult.†

* See, e.g. British patents 279068 and 279937.

† See H. H. Poole and W. R. G. Atkins, *Journ. Marine Bio. Ass.*, xv, 455 (1928).

Modulation.

When pictures or scenes are transmitted by wireless, the photoelectric currents have to modulate the transmission. The usual plan is to amplify the currents in the manner already discussed, and to use them exactly as voice-currents are used in any of the methods employed for modulation in radio-telephony. But more direct methods have been suggested. Thus, as we saw on pages 77-78, a gas-filled photoelectric cell is equivalent, for small changes of potential, to a conductor of which the conductance is proportional to the light. If, therefore, the cell is used as a grid leak, or as part of a potentiometer inserted in an appropriate part of the transmitting circuit, the output will be controlled by the light falling on the cell as it would be by changes in the resistance of an ohmic conductor placed in the same position. It must not be assumed, in designing an arrangement of this kind, that the conductivity of the cell for high-frequency currents is that calculated from the voltage characteristic; but no information seems to be available from which the variation of the conductivity with frequency might be deduced. Another similar proposal is to use the cell as the condenser in a tuned loop forming part of the transmitting circuit. The dielectric constant of the gas in the cell increases with the ionization, and therefore with the light; the capacity of the condenser and the natural frequency of the circuit vary therefore with the light; but, again, nothing is known quantitatively concerning the variation.

In some systems of radio-picture telegraphy two carrier frequencies in series are employed. The radio-frequency (of the order of 10^7 cycles) is modulated by a high audio-frequency (of the order of 10^4 cycles), and this in turn is modulated by the low audio-frequency photoelectric currents resulting from alternations of light and dark in the picture. In such systems the high audio-frequency carrier is usually generated photoelectrically, by inserting in the path of the light a disc pierced with holes rotating at a very high speed; but there are considerable mechanical difficulties in obtaining sufficiently high frequencies by this means. It has been suggested that the high audio-frequency carrier might be generated in the cell by the use of intermittent currents according to the principles of Chapter VII; but the difficulties of maintaining constant frequencies are grave.

CHAPTER XII

SPECIAL METHODS

Other Ways of Measuring Current.

THE methods discussed in the last two chapters were classified according as the current is measured by its electromagnetic or its electrostatic effects. But there are methods of measuring current that fall into neither of these two classes. Thus, it can be measured electrolytically, a method that might be suitable if the problem were to integrate the amount of light received over an extended period; such a problem arises in some biological applications (see page 181). Attention may be drawn to the ingenious, but neglected, mercury drop coulometer.*

Again, the use of the flashing neon tube (see page 83) has been proposed.† The principle is precisely the same as that of the ticking electroscope (see page 124). A condenser is charged up to the glow potential of the tube by the current through the cell, and is then discharged in a visible flash. The number of flashes corresponds to the number of ticks; E is the difference between the glow and stopping potentials. The method was proposed for use on board ship when only rough measurements are required; it may have uses in other similarly difficult circumstances; but, even if specially-designed neon tubes are used, it is unlikely that much precision could be attained.

Use of the Glow Potential.

In the remaining methods the magnitude that is measured, compared, or detected is not the current under an approximately constant voltage, but some other characteristic of the cell variable with illumination.

One of these is the glow potential, which varies with the light; the manner of variation is easily deduced from dia-

* C. T. R. Wilson, *Proc. Camb. Phil. Soc.*, xix, 345 (1920). For more usual electrolytic methods, see I. Ranzi, *Nuovo Cimento* 5, 234 (1928); W. R. G. Atkins and H. H. Poole, *Proc. Roy. Dublin Soc.*, xix, 159 (1929).

† H. H. Poole, *Nature*, 121, 281 (1928).

grams similar to Fig. 14. Fig. 38 shows the relation for the plane cell and the spherical cell to which Fig. 17 refers; it will be appreciated at once that for this method the spherical cell is more suitable. But with any cell regularity is difficult to obtain, because the glow potential always depends

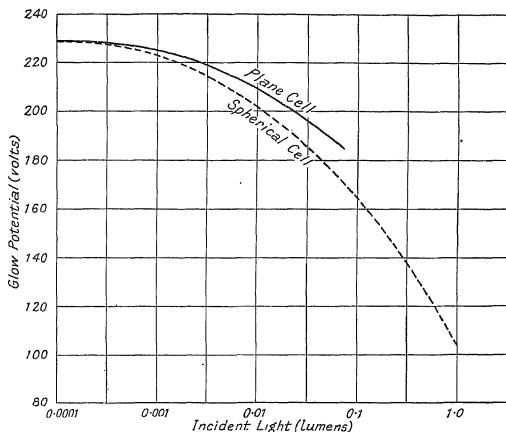


FIG. 38. VARIATION OF GLOW POTENTIAL WITH ILLUMINATION

slightly on the previous history of the cell, especially at low illuminations.

The glow potential has been used in two ways. In one a constant voltage above the stopping potential is applied to the cell, and the light incident on it increased till the glow starts; it is then known that the light has attained a fixed value. In the other the voltage is raised gradually, and the potential at which the discharge occurs noted. Both of these methods (which are essentially detection) lend themselves readily to the making of records in accordance with the principle of page 109.

Another method that has been proposed is to use a gas-filled cell as a Geiger counter.* If the voltage between electrodes immersed in a gas at low pressure is maintained just below the glow potential, the production of local ionization between them, caused by the entry of an ionizing particle, may give rise to a momentary discharge, which ceases again when the local ionization ceases; in suitable circumstances, the frequency of the discharges may be equal to the frequency of the entry of an ionizing particle, and the number of such particles may be counted. In a gas-filled cell the primary electrons may be the ionizing particles, and in ideal circumstances they might be counted individually. This method is certainly the most sensitive that has been devised, but is very difficult; no actual use seems to have been made of it so far, but it certainly deserves consideration by those to whom sensitivity of measurement is the first consideration. It should be distinguished from a method that we are about to discuss, in which the incidence of light stops (in place of causing) intermittent discharges.

Intermittent Currents—Small Illuminations.

But we believe—though parental prejudice may blind us—that the most useful of these special methods is that which employs the critical illumination for intermittence, according to the principles of Chapter VII. It is especially suitable for detection associated with control, because the intermittent currents are so easily amplified; but it may have uses apart from amplification.

One of these is the detection or comparison of illuminations so small that the only alternatives are highly sensitive electrostatic methods or very large amplifications by means of valves. Over these alternatives the method of intermittent currents has the advantage of great simplicity, and almost complete freedom from external disturbances. A constant source of potential is not needed and observations can be taken, by means of a telephone, at almost any distance from the cell; the telephone is preferably connected to the

* J. Elster and H. Geitel, *Phys. Zeits.*, xvii, 268 (1916); E. Steinke, *Zeits. f. Phys.*, xxxviii, 378 (1926).

For an account of the Geiger counter, see H. Geiger and O. Klemperer, *Zeit. f. Phys.* xlix, 753 (1928), who give earlier references.

secondary of a transformer, the primary of which is in series with the cell and current-limiter. A spherical cell must be used, and, for the best results, careful selection must be made even among cells of the same type; for the dark current, which imposes the sensitivity limit varies widely, and so far inexplicably. The sensitivity limit can be reduced to 10^{-9} lumen.

Two variants of the method may be employed. In one the current controlled by the current-limiter is varied until intermittence just sets in, or rather till the clicks in the telephone assume some standard slow rate—say one a second. In the other the current is kept constant, and the light varied till the standard rate is attained. The second alternative is the more sensitive, but the less convenient. Both these methods are comparative only, and serve to establish equality between two amounts of light entering the cell. Measurement is, theoretically, possible by the use of the relations of Figs. 21 and 22, but it would probably have little accuracy.

Of practical details only two need be mentioned. The insulation of the cathode of the cell must be good; the resistance between it and the rest of the circuit must be certainly greater than 10^{12} ohms. Again much depends on the correct adjustment of the capacity C . It should be increased gradually from zero until further increase produces no considerable decrease of the least current which will give rise to intermittence; the value required will probably be about $100\ \mu\mu\text{F}$. A variable condenser such as is used in wireless sets will do if the insulation is good enough. A simple and effective alternative is a glass tube wrapped on the outside with tin-foil; mercury, poured into the tube until the capacity is right, forms the other "plate."

Intermittent Currents—Large Illuminations.

But the scope of the method is greater when lights of the order of 0.1 lumen can be thrown on the cell, a precision of 10 per cent is necessary, and the control of subsidiary mechanism is required. A plane cell is then suitable.

The circuit is shown in Fig. 39. For the purposes of adjustment it is convenient to insert a microammeter in series with the cell, and to place a telephone in parallel with

the transformer; but these may be removed when the adjustment is complete.

For the controlling diode a bright emitter is preferable to a dull emitter, and a type is best in which the anode and grid leads are not brought out through the same seal as the filament leads. The insulation resistance between the valve anode and the rest of the circuit must be at least 1,000 megohms. These parts are best enclosed in an earthed metal box, the interior of which should contain a drying agent if the apparatus is to be used in damp places. The remainder of the circuit requires only ordinary insulation, and the box

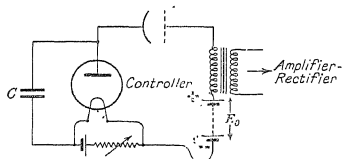


FIG. 39

can be joined to it by many feet of "flex." Concerning the condenser, the remarks of the last paragraph are applicable.

The high-tension supply need not be even approximately constant, but E_0 must always be greater than the maximum glow potential of the cell. Rectified alternating current from mains, smoothed by condensers, serves admirably.

The filament current should be controlled by a finely variable rheostat and should be set so that the current i through the cell and valve, read on the microammeter, corresponds to the maximum of the curve in Fig. 20. That is to say, the current should be such that the greatest possible light (L_m) is required to stop the intermittence. In one sense the apparatus is then in its least sensitive state, because the largest light is required to operate it; but in another, and more important sense, it is in its most sensitive state. For when detection is by means of a relay, the critical light is not that which makes the intermittence just vanish and reduces the output current to zero, but that which reduces it to the point at which the relay opens. For sensitivity, it is necessary that the rate of change of the rectified

current with light should be as great as possible in the neighbourhood of the critical light. Nothing was said in Chapter VII about this matter; and there is no need to attempt a theory of it here. Actually, the rate of change will be greatest when the current through the cell is adjusted as described. Another advantage of this adjustment is that the critical light varies slowly with i , so that great constancy of the filament current is not essential to precision.

The coupling between cell and amplifier should be an iron-cored, inter-valve transformer with the high impedance side connected to the cell. It must not be placed in the earthed return of the high-tension supply, for in that position the current from the condenser would not pass through it. The transformer and amplifier treat separately each impulse arising from a discharge through the cell; the duration of these impulses is independent of, and short compared with, the interval between them. The frequency to be amplified is not that which was discussed on page 87, but that determined by the duration of the impulses. It is of the order of 10,000 cycles per second, and is independent of i . No special arrangements are necessary, therefore, to make the set suitable for low frequencies, or to make the amplification independent of the frequency.

The valves should be of the power type and capable of dealing with large grid voltage swings. With one amplifier and a rectifier, the maximum anode current, when the cell is dark, will be of the order of 10 mA., and sufficient to work a mechanical relay of the telephone type.

A limit to the speed of response is set by the frequency of intermittence; the set cannot detect a change in light lasting much less than the interval between two discharges, which will be of the order of $1/300$ second; if a relay is used, the limit will probably be about $1/10$ second. If L_1 and L_2 are the lights at which the relay opens and closes, $L_1 - L_2$ is determined by the relay rather than by the cell or amplifier. But the constancy of either L_1 or L_2 (which determines the precision of detection), with a good relay, is fixed by the consistency of the cell and the constancy of i . If the filament currents of the valves, controlling, amplifying, and rectifying, are subject to the variations of supply mains, L_1 and L_2 may vary by as much as 10 per cent, but if they

are supplied from batteries, or other constant current device, the variation need not exceed 1 per cent.

If the light to which the relay has to respond is considerably less than the maximum of Fig. 20, the plane cell loses its advantages and the spherical becomes preferable. For very small lights a spherical cell must be used, as explained on page 159. The frequency of intermittence will now be greatly reduced; but when rapidity of operation is unnecessary, the same apparatus can be used if a relay, sufficiently sensitive but very slow acting, is employed. A suitable relay can be made to work when the frequency of intermittence is less than 1 per second, and will detect, in conjunction with the remainder of the circuit just described, a light of 0.0001 lumen—much less, it is to be observed, than that within the range of the detector of pages 144, 145.*

Priming.

Lastly, it may be pointed out that the form of Fig. 16 (page 72) shows that, if the mere detection of light is required, it may be desirable to "prime" the cell by a constant illumination, so that an increase of illumination carries the cell from the lower to the upper part of the curve and causes a great increase in current. This method is especially suitable with plane cells in which the priming illumination is comparatively small.

* See British Patent Application 17001/28. The relay consists essentially of an unbalanced lever pivoted on a nearly vertical axis. It is retained in a position of unstable equilibrium by the attraction of a magnet which receives the intermittent current. If the current ceases, the lever swings round, slowly at first, but gathering momentum, and completes an electric circuit.

PART III

THE APPLICATIONS OF PHOTOELECTRIC CELLS

IN accordance with our decision on page 102, we were concerned in Part II with methods of measuring, comparing, or detecting the amount of light incident upon the cell. We have now to consider the relation between this amount of light and the ultimate cause; we have to ask how the variations, the study or use of which provides the incentive to using photoelectric cells at all, are best translated into variations in the amount of light entering the cell. In many applications this is the most important part of the problem; but even when it is unimportant and the answer is obvious, the question provides a convenient method of classifying the applications. We cannot pretend that in the following pages we have mentioned all the applications that have been made, and still less all that have been proposed, but we have mentioned all of which we have found an account in likely places. It seems that in all of these the thing studied or used, and the ultimate cause measured, compared, or detected, falls into one of the following classes, to each of which a chapter will be devoted—

1. Luminous flux.
2. Illumination.
3. Colour.
4. Absorption.

but the former are unimportant, and the latter are dealt with in a manner considered below.) In principle the photoelectric cell ought to be used only to compare lamps at the same temperature; but in practice this limitation can be removed in two ways. If the range of quality is small, cells, or combinations of cells and filters, can be found which do agree with the eye to the necessary precision within this small range; in this way the whole range of commercial tungsten lamps, from the vacuum lamp of lowest temperature to the gas-filled lamp of highest temperature, can be measured without correction to an accuracy of $\frac{1}{2}$ per cent. Alternatively, the spectrum (or, for incandescent lamps, the temperature) can be determined independently, and an empirical correction introduced for the difference between the test lamp and the standard to which it is referred.

Next there are complications arising from the lack of uniformity of photoelectric cells. A single eye can view at the same time two surfaces illuminated by different sources, and compare their brightness. But a single cell cannot distinguish light from one source from light from another; to compare different sources in a strictly analogous manner, the lights from them would have to be thrown on two different cells; the emission of these cells will not be exactly the same, and equality of the currents will not indicate equality of the lights. If equality of currents is to indicate equality of light, the lights must be thrown alternately on the same cell; the only visual method that can be adapted immediately to a photoelectric cell is the little used method of flicker.

In most of the more precise methods of photoelectric photometry some modification of this method is used. But almost as important as the difference in the emission of different cells is the difference between different parts of the same cell. Thus, if we are trying to use the inverse square law, we shall set up a cell behind an opening of fixed area in a screen, and vary the distance of the source from this screen until the current through the cell attains some fixed value. But unless the screen is in contact with the cathode, or at least at a distance from it very small compared with the distance of the source (conditions almost impossible to attain in practice), the area of the cathode covered by the light

passing through the opening will vary with the distance of the source; if the emission of the cathode is not perfectly uniform over its surface, equality of current will not indicate equality of light coming through the opening. The same difficulty enters if we are using a sphere for measuring total luminous flux. The brightness of the surface of the sphere is independent of the distribution of the flux from the lamp; but if the cathode of the cell is not a portion of the wall of the sphere, but merely placed behind an opening in it, the distribution of the light over it may vary appreciably with the distribution of the flux from the source. Further, it is not certain that, even if the cathode were part of the wall, the current would be independent of the distribution of flux; for the relation between the angle of incidence of the light and the resulting emission is not the same as that between this angle and the resulting brightness of a perfectly diffusing surface.

The errors arising thus from the lack of uniformity of a single cell are not very serious; methods have been used in which no attempt has been made to remove them, and yet a precision of about 1 per cent has been attained; but they are appreciable when the highest precision is sought. We can suggest no method of removing them completely, but they can be reduced to a point where they are masked by other errors, if a device for diffusing the light is introduced between the cell and the aperture in the screen or in the sphere illuminated by the source. The best device, shown in Fig. 40, is another sphere. The sphere S' receives light from the source through the aperture A , which is directly illuminated by the source if the intensity in a given direction is being measured, or forms part of the wall of the sphere S containing the source (as shown in the figure) if total flux is being measured. The cell is placed behind the second aperture B . The light received by the cell is, of course, considerably reduced, but is still amply sufficient when lamps of 10 watts and upwards are to be measured. If two cells are used, in order that their resultant emission curve may resemble the visibility curve (see page 50), they can both form part of the wall of S' .

In lamp photometry, total flux is of much more importance than intensity in a given direction. Accordingly, we

shall assume that the flux from an aperture in a sphere in which the source is enclosed is the quantity that has to be measured; the modifications possible or desirable when the aperture is in a screen on a photometer bench are too obvious to require discussion. Analogy with the usual visual method suggests that this flux should be balanced against that passing through an aperture in a screen on a photometric bench illuminated by a comparison lamp, and measured by the inverse square law applied to that lamp.

If the sources of error that we have just discussed could be neglected, this comparison could be effected most suitably by the revolving mirror method of page 153; the fluxes would be alternately thrown directly on the cell, and the balance judged by the vanishing of the alternating component of the photoelectric current. Since the fluxes have a different distribution, there would be some difficulty in securing the necessary condition for a complete balance, namely, that the rate of decrease of one flux should be always equal to the rate of increase of the other; but this would affect only the sensitivity of the method. But the lack of uniformity of the cell would introduce systematic errors and inaccuracy. Though the method has been used, it is not recommended if precision greater than 1 per cent is required.

To remove the systematic error, the light from the apertures may be diffused by the arrangement of Fig. 40. A second aperture A' is provided in S' in a plane perpendicular to those of A and B ; A coincides with the aperture in the sphere, A' with that in the screen of the photometric bench.

With this arrangement, it would be illegitimate to assume that equality of the fluxes entering the cell is an indication of equality of the fluxes passing the apertures; but if the apparatus is calibrated (as it is in precise visual work) by replacing the test lamp in the sphere by a standard, this assumption is not necessary. It is only necessary to assume that the balance indicates that the fluxes passing the apertures are in a ratio independent of their absolute magnitude. This assumption is safe, so long as the fluxes are of the same quality; if they are not, selective absorption by the "white" paint of S' might introduce error; but, since errors of this kind are inherent in any method in which illumination

from a sphere is compared with direct illumination, it may probably be neglected.

With this modification the method is accurate, though the difficulty of securing a true balance will still cause loss of sensitivity. But it now becomes much more difficult to solve the mechanical problem of alternating the two fluxes with a sufficiently high frequency; for nothing less than 50 cycles per second is desirable. An alternative is the commutation method of page 105, probably applied to the output of a direct-current amplifier (see page 140); if the transformer modification is used, the processes involved during the change of flux are immaterial. Here the difficulty is to find a suitable commutator.

Departures from Visual Methods.

We see then that it is not very easy to convert the well-established visual method into a photo-electric method retaining its chief characteristics; these are that it is a null method of comparison, accurate in principle, in which measurement is based on the inverse square law. We must now consider whether anything is gained by abandoning any of them.

The only methods that can be considered for this purpose serious rivals to the inverse square law, as a means of producing a known continuously variable flux, are those employing shutters or their equivalents (see page 192). The comparison lamp, like the test lamp, might be enclosed in a sphere provided with a shutter of variable aperture, and this aperture might be substituted for that in the screen on the photometer bench. This change would solve partially some of the difficulties that we have been discussing, because the greater similarity of the distribution of the light from the test and comparison lamps would make it less necessary to use the sphere S' . Less inaccuracy, and probably less insensitivity, would be incurred by using the revolving mirror method and reflecting the two lights directly into the cell; some must remain because the two distributions would not generally be identical; we have no information on which to

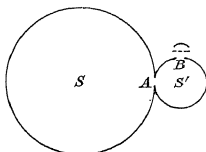


FIG. 40. DIFFUSING SPHERE ARRANGEMENT

judge how great it would be. An iris diaphragm would probably be most suitable as a shutter; it would need calibration; but on the other side is to be set the gain of avoiding the cumbrous photometer bench. It should be noted that the sector disc, which needs no calibration, could not be used; for its frequency would need to be great compared with that of the alternations of the light, and such a frequency would hardly be attainable.

Accuracy in principle might be sacrificed by throwing the lights from the comparison lamp and from the test lamp on different cells, and using the balance method of Fig. 24; the indicating instrument would be either an electrometer (see page 118, or a direct-current amplifier (see page 132). The sensitivity of this method would be very great; its accuracy would depend on the constancy of the effective emissions of the two cells. It could never be assumed, of course, that their effective emissions were equal; but if the apparatus were calibrated, as usual, by the substitution of a standard for the test lamp, it would be sufficient if the ratio of these effective emissions remained appreciably constant during the interval between calibrations. Now this condition can be secured, even when calibrations are not made more than two or three times a day; but it is also possible to secure that each emission, and not only the ratio of the two emissions remains constant for long periods; and when such constancy of each emission can be secured, other and more convenient methods are available (see page 172). For this reason it is very doubtful whether anything is gained by a method which merely demands constancy of the ratio. Possibly it might permit the employment of gas-filled instead of vacuum cells but gas-filled cells lose their superior sensitivity when a balance method is employed (see page 104). Accordingly, we cannot see any real justification for this method, although it has occasionally been employed.

Next we might cease to demand that the method of comparison is null. (Indeed, it is not certain that the visual method is properly classified as null.) We might adopt any method in which the reading of an indicating instrument varies with the flux on the cell, read the instrument when the comparison lamp is cut off, and then set the comparison lamp so that the same reading is reproduced when the tes

lamp is cut off; probably an electrometer across a high resistance would be the most suitable indicating instrument. The method would certainly be slow and suitable only for careful observers; but for occasional observations it has the great merit of simplicity of apparatus.

A modification of this method has been proposed that sacrifices the last merit, but substitutes the advantage of a permanent record. It depends upon "bracketing" the test lamp between two standard lamps (or possibly two positions of the comparison lamp) not very different from it. The form of it that has been developed with great care and elaboration employs the constant time method of page 109. A recording quartz-fibre electrometer is alternately earthed and insulated by an automatic mechanism; during the period of insulation, the fibre is momentarily illuminated at accurately-timed intervals, so that the record shows a series of dots, a line through which indicates by its slope the rate at which the charge accumulates. During the succeeding earthed period, the lamp is changed. Successive series of dots thus refer to different lamps; in the interpretation of the record, all that has to be assumed is that the characteristic of the cell remains unchanged during the interval covering the measurement of the test lamp and of the two standards, one greater and one less, by which it is immediately preceded and followed. In order to interpolate between these standards, it is assumed that over the small range concerned the rate of deflection is proportional to the light. It is unlikely that such a method will ever find a use outside standardizing laboratories of the first class; but it is doubtless capable of very great precision. The relative sensitivity is determined by the ratio of the width of the dots to the total deflection of the fibre; something better than 1 in 1,000 is claimed, and nothing more would be useful in view of the inconstancy of all lamps. Systematic error seems to be completely excluded if the test and standard lamps are of the same type and inserted in the same sphere.

Lastly, we may abandon comparison altogether, and substitute direct measurement of the photoelectric current. The possibility of success in this direction depends entirely on the quality of the cell. The emission must be strictly constant, both in time and in respect of variations of the light;

that is to say, the photoelectric current must be accurately proportional to the light, and the constant of proportionality must not change so rapidly that calibrations have to be made with undesirable frequency. This condition demands either vacuum cells or gas-filled cells used at a magnification so low that their effective emission is little greater than that of vacuum cells; but this is not a serious disadvantage when lamps of ordinary commercial types are concerned, for ample sensitivity can be obtained by suitable methods of measurement. Until recently, it would have been difficult to find in the market cells, even vacuum cells, of the requisite constancy; improvements in manufacture, and in particular the introduction of thin film cells (see page 34), have now produced cells equal to the severe demands that this method makes upon them; but it is necessary to make sure that suitable cells have been obtained before embarking on this method.

Those who have developed this method employ for the measurement of the current the direct-current bridge amplifier, in which the photoelectric current is compensated by a variable grid bias (see page 142), and attain a precision of at least $\frac{1}{4}$ per cent. The apparatus consists of a large sphere *S* containing the test lamp, and a small sphere *S'* containing the cell, as in Fig. 40. The cell is connected to the amplifier. The ratio between the flux of the test lamp and the grid bias necessary to balance the bridge is determined by inserting standard lamps in the sphere. In setting up the apparatus it is, of course, necessary to use several standards to make sure that the flux and grid bias are truly proportional; but when once it is in working order, a check on one standard, or at most two, a few times a day is sufficient. In order that the potentiometer may be calibrated directly in lumens, independently of any slow and small changes that may occur in the emission of the cell or in the reflecting power of the spheres, the resistance through which the grid bias is applied is variable (see page 143). This is the method which appears to find favour for the routine measurement of large numbers of lamps among those who have studied photoelectric photometry most closely. It has the advantage of abolishing the comparison lamp and, therefore, the troublesome second electrical circuit, which has to be kept strictly constant.

Calibration.

The lamps used for the calibration of any photoelectric photometer will always have been compared with the basic standards, and usually with each other, by visual methods. There is a certain anomaly in calibrating a more precise method by a less precise, but here it is unavoidable. For these lamps will usually differ from each other and from the basic standards in colour; the comparison of lights of different colour must ultimately be visual, because the equivalence of differently coloured lights in respect of intensity has no meaning apart from the peculiar properties of the eye. The eye need not enter into every comparison; we might, for example, determine the relation between energy and wavelength in the spectrum of the source and then deduce its visual effect from the visibility curve, which, of course, is determined by a long series of observations on many eyes; but it must enter somewhere, and there is actually little to be gained in making its entry less rather than more direct.

When the law on which the calibration is based is one of which the form is known accurately, the precision may be much greater than that of the standards. Thus, if all lamps are of the same colour, and we measure by the inverse square law or by the constant ratio of photoelectric current to flux, the relative precision (i.e. the error in the ratio of any two lamps) will not depend on the precision of the standards at all; and the absolute precision can be raised above that of any individual standard if a sufficient number of standards is used, and the differing results they give adjusted suitably in adopting the final calibration. If lamps of different colour are concerned, and if the precision of comparing visually lamps of the extreme colours is less than the precision of the photoelectric method for lamps of the same colour, it is not certain that a precision higher than that of each visual standard can be obtained; but some increase in precision may be attained by multiplying the number of standards, and distributing those of the same colour uniformly over the range of intensity.

The position is much less favourable when the law on which the comparison is based is empirical, as it would be in the shutter method of page 169; it is not then certain

that increase in the number of standards will lead to a precision greater than that of each standard, though the probability of such increase will be greater if the law concerned approaches nearly some very simple form, e.g. is nearly linear.

It may be well, therefore, to point out that, by using the second law of photoelectricity, it is always possible to calibrate for relative values of lamps of the same colour, without relying on any methods less precise than those to which the calibration is to be applied. When these relative values are fixed, the form of the law is known; absolute values, and relative values for different colours, can then be determined as before.

The principle is best explained by an illustration. Suppose the sphere S' (Fig. 40) has three apertures, one of which leads to the cell, another to a sphere S_1 , and the third, provided with a shutter, to a sphere S_2 . Two lamps L_1 , L_2 are placed in S_1 , and a third L_3 in S_2 . The shutter is set at x_1 ; L_1 (say) and L_3 are then adjusted by means of the circuits that feed them, so that a balance is obtained; L_1 is now turned off, L_3 left unaltered, and L_2 adjusted so that it also balances L_3 . L_1 and L_2 are now turned on together at their adjusted values, L_3 being still unaltered, and the shutter moved till a balance is obtained at a reading x_2 . Then it is known that the flux corresponding to x_2 is double that corresponding to x_1 . By finding pairs of values of x , such that one corresponds to double the flux of the other, a complete calibration can be obtained by suitable methods of computation. In practice it is better to use more than two lamps in S_1 ; a lamp with (say) 6 independent filaments enables sets of values of x to be ascertained, corresponding to fluxes in the ratio of 1, 2, 3, 4, 5, 6. It is important to observe that the method does *not* involve the assumption (which is usually false) that L_1 and L_2 , when both adjusted to balance L_3 , give the same flux; it involves only the assumption that the flux from L_1 is not changed by the simultaneous lighting of L_2 . Nor is it necessary that L_3 in S_2 should fulfil accurately the conditions necessary for the measurement of total flux by a sphere; it is only necessary that L_3 , i.e. the comparison lamp, should occupy the same position during calibration as during use.

(b) STARS

Stellar photoelectric photometry has an interest for those who are not astronomers, because it involves the measurement of very faint lights and requires the attainment of the least possible absolute sensitivity limit. Our complete innocence of astronomical knowledge would, in any case, forbid us to discuss it from any other standpoint; but a few introductory remarks are necessary to indicate what is demanded.*

The chief problem is the determination of the light-curves of variable stars; for this purpose a precision of about 1 per cent is required. The work of applying photoelectric methods will hardly be justified unless they can deal with stars as faint as the fifth magnitude, and an extension to the sixth is highly desirable. A first magnitude star gives at the earth's surface about 1.7×10^{-5} lumens per square metre. The surface of the telescope objective used for this work will not generally be much more than 0.5 sq. metre. A sixth magnitude star gives $(2.612)^{-6} = 0.004$ times the flux of a first magnitude star; consequently, the flux at the focus of the telescope, which has to be measured to about 1 per cent, is about 3×10^{-8} lumens. If the light is of the colour of daylight, a primary photoelectric current of at least 10^{-13} amp. can be obtained.

In the laboratory it would probably be possible to measure this with the required precision without magnification by gas-filling. But in an observatory conditions are not so favourable. The entire measuring system has to be carried on a telescope, so that electrometers that need a stable base are excluded, e.g. the Compton and Hoffmann electrometers. Furthermore, the air of the observatory cannot be warmed, and high insulation is not easily maintained. Accordingly, no serious attempt seems to have been made to use vacuum cells, which are alone really suited to precise measurement; comparatively low electrical sensitivity has been accepted

* The following papers discuss the methods, apart from the results, of stellar photometry. The purely astronomical papers concerned primarily with results, do not generally give details concerning methods to be of interest to others than astronomers—

P. Guthnick, *Verh. d. Deutsche Phys. Ges.*, xvi, 1021 (1914); *Zeits. f. Instrumentenkde.*, xiv, 303 (1924). G. Rougier, *Révue d'Optique*, ii, 133 and 365 (1923). E. Bonty, *Révue d'Optique*, v, 31 (1926). H. Rosenberg, *Zeits. f. Phys.*, vii, 18 (1921).

as inevitable, and efforts have been concentrated on obtaining the highest possible effective emission from the cell by using high magnifications.

An ultimate limit in this direction is set by the "dark current," due to the incipient corona discharge (see page 63). But a matter that has received almost more attention is the variation of the emission with the previous history of the cell (see page 37), generally (but erroneously) called fatigue. The only certain way to overcome it is to keep the illumination of the cell always constant by reducing the lights from all stars to the same intensity with screens of known absorption, and by throwing artificial light on the cell while it is moved from one star to another. However, while methods of overcoming troubles arising from these two sources have been examined with great care, methods of removing them altogether have received far less attention. As already explained, no investigation seems to have been made concerning the type of cell which gives the greatest magnification before the dark current appears; nor has the possibility been properly explored of using a cathode less subject to variation under the discharge than sensitized potassium, even if it involves some sacrifice of sensitivity. Many astronomers have been driven to making their own cells, but they seldom publish details of their methods or results; closer co-operation between makers and users of cells is highly desirable.

For the electrical measurements, one of the two direct-reading methods of page 109 is always adopted. The highly sensitive methods mentioned on pages 158-159 are worth consideration, but they are probably insufficiently accurate.

The electrometer is usually one of the fibre type suspended so as to keep a constant relation to the vertical. The Lindemann electrometer, quite independent of gravity, though designed for this purpose, has not yet come into general use. It is a little surprising that compensation methods are so seldom used, for they undoubtedly render the insulation problem easier and avoid all questions concerning the scale of the electrometer; but they have not found favour, except possibly for the compensation of the dark current. The induction method of compensation (see page 114) would seem to present advantages, because the calibration is so simple and accurate. It should be observed

that any method of compensation by, or comparison with, an artificial light does not here lead to an increase in accuracy; for, owing to variable atmospheric absorption, the test star must always be compared with a standard star to which the telescope is turned before and after measurements on the test star; the artificial light could act only as a comparison lamp, not as a standard. It must be remembered that the emission varies over the surface of the same cathode, and that the image of the star (always greatly out of focus) must always fall on exactly the same part of the cathode. There is no difficulty in fulfilling this condition.

Finally—though it is not strictly relevant to our subject—the question why photoelectric methods are attempted at all requires an answer; to the outsider photographic photometry would seem so much more suitable. We understand that the answer lies in the distinction between sensitivity and accuracy. The photographic method is much more sensitive; images of very faint stars can, of course, be obtained, and their density measured; but the relation between the density of the image and the magnitude of the star is so complex that error is apt to enter with the transition from one to the other.

(c) SPECTROPHOTOMETRY

Photoelectric methods can be used to determine the intensity of spectral lines. When nothing more is required than a comparison of the intensity of the same line emitted by different sources, the problem is quite simple. If the sources to be compared can be interchanged rapidly before the slit of the spectroscope, any of the methods suitable for measuring absorptions can be adopted (Chapter XIV). If they cannot, and if it is necessary to be sure that the same measured current through the cell corresponds to the same light falling upon it over considerable periods, a vacuum cell and electrometer with compensation by induction (see page 114) is probably the most suitable method, unless the light is so great that a galvanometer can be used.

But when the intensity of different lines is to be compared, great difficulties arise in calibration. The magnitude to be determined is the power carried by the radiation

emerging from the slit; to deduce this from the current in the cell, the emission of the cathode in amperes per watt has to be known. This emission, as we have seen, varies greatly, not only with the wavelength, but with the nature of the cathode and with the particular cathode, and even with the particular place on the cathode which the light strikes. Calibration is, therefore, necessary under the exact conditions of use, and the problem is necessarily reduced ultimately to a comparison of the lines in the source under examination with those of the same lines in some other sources of known spectral distribution. In fact, measurements of the current given by a cell exposed to different lines from a spectroscopic are made most often when the primary object is to calibrate the cell and to determine its emission curve. Here, since absolute measurements of current are required, compensation by induction has special advantages. If the light is sufficient, a galvanometer or the bridge amplifier with compensation by the grid resistance (see page 142) are possible alternatives. The direct-reading electrostatic methods often used are tolerable only if no precision is attempted, and, even then, they have hardly the merit of convenience.

(d) MISCELLANEOUS

The measurement of the light from phosphorescent substances and from gas discharges may be mentioned as illustrations of the use of photoelectric methods in purely scientific investigation. Pyrometry, or the measurement of temperature by the quantity of light emitted from an incandescent body, is another possible field, but one that that has yet to be explored.*

* See A. Pospelow, *Ann. d. Phys.*, xlv, 1039 (1914) (phosphorescence); E. V. Angerer, *Phys. Zeits.*, xxii, 97 (1921) (gas discharge); U.S. patent 1626663 (pyrometry).

CHAPTER XIV

ILLUMINATION

Daylight.

METHODS for measuring luminous flux can always be adapted to measuring illumination; indeed, when the area through which the flux is received is constant, illumination is the magnitude measured primarily, and the flux is deduced from it. But the illumination of daylight, or its artificial substitutes, has peculiar features that make special methods suitable. First, there is practically no limit to the amount of light that can be thrown on the cell, or, therefore, to the photoelectric current, if the area of the cathode can be sufficiently increased. Cells so large that they give a current of a milliampere or more when exposed to daylight out of doors have been used for daylight recording. With such cells all the usual difficulties attendant on the smallness of the current vanish, and the problem becomes almost one of electrical engineering. Such cells are, of course, expensive; but on the other hand, the associated apparatus is cheap.

Second, the changes to be measured or detected are usually very slow and very large, so that no great speed or precision is required. If non-automatic measurement is required, there is probably never any advantage in adopting photoelectric methods at all; visual observations will always be more convenient and sufficiently precise. And when record is necessary or detection must be associated with control, methods, unsuitable elsewhere, may be adopted on the ground of their simplicity. Thus a use has been suggested here—and only here, so far as we know—for the variation of the glow potential with light (see page 157). A recording electrostatic voltmeter and a large condenser are connected across the cell; they are charged up by any source of sufficiently high direct-current voltage through a large resistance. The recorded voltage rises to a peak at the glow potential, and then falls suddenly as the cell discharges, tracing out the cycle of page 81 very slowly; a curve drawn through the peaks indicates the variation of the illumination, when

the relation between illumination and glow potential has been established by calibration. Again, for the control of an operation (such as the turning on of lamps) that has to be performed when the illumination passes through a critical value, the simplest amplifying circuit of all (see page 145) will probably be quick and precise enough. Devices of this kind to switch street-lighting on and off are a favourite theme of the amateur inventor; the objections to them are not technical, but commercial; the device has to be very cheap and simple if it is to be repaid by the cost of the power saved.

However, the measurement of daylight may also present very difficult problems. Perhaps the most difficult that has been attacked so far is the measurement of the penetration of sunlight into the sea. Here the necessary apparatus has to be separated by considerable distances from the cell, and the motion of the ship from which observations have to be made excludes many methods otherwise suitable. Valve amplification naturally suggests itself, for external disturbances should be easily avoided; but, actually, other devices have been preferred.*

The measurement of the exposure of photographic shutters is a problem to which photoelectric methods seem clearly suitable; the total charge passed through the cell during the exposure would give a direct measurement. But though this method has been proposed several times, we have not found any account of its use. Here the difference between the visibility curve and the emission curve of the cell need not enter, since the constant illumination could be measured with the same cell. But, generally, in the measurement of daylight, as in the photometry of lamps, allowance for this difference has to be made, and may greatly complicate the problem.

Radiation-therapy.

The determination of the proper dose in medical treatment by means of "artificial sunlight" is another application of increasing importance.† It demands either the measurement

* See H. H. Poole and W. R. G. Atkins, *Journ. Marine Biol. Ass.*, xiv, 177 (1926); and xv, 455 (1928).

† H. D. Griffiths and J. S. Taylor, *The Lancet*, ccix, 1205 (1925); C. Dorno, *Strahlentherapie*, xxv, 351 (1927); A. Rüttenhauer, *Strahlentherapie*, xxvii, 794 (1928).

of the output of the lamps used, or of the illumination they produce on the patient's body. We shall take the latter form of the problem; the modifications necessary to adapt methods to the former are quite obvious.

It is known—or assumed—that the proper dose is given when D has some prescribed value, where

$$D = \theta(\lambda) \frac{P}{S} t \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

t is the time of exposure of the patient to the radiation, P the power carried by the radiation incident upon area S of his body, and $\theta(\lambda)$ a function of λ , the wavelength of the radiation. (It is not clear to us how this formula would have to be affected if the area of the body exposed were changed; but that is irrelevant to our problem.) The common practice in determining the dose is to measure each of the three factors on the right of (1) separately. If the radiation were visible, the second factor, P/S , would be proportional to the illumination at the surface of the patient's body, and may here be called the illumination L . The problem of measuring it photoelectrically is precisely similar to that of measuring the visual illumination.

If a cathode of constant effective area is exposed in the same position relative to the source as the patient, the primary photoelectric current i will be proportional to L so long as λ is unchanged. But if λ varies, i will be proportional to $\sigma(\lambda)L$, and we shall have

$$D \propto \frac{\theta(\lambda)}{\sigma(\lambda)} it.$$

If the dose is to be measured by it —and this is the ideal—when λ varies, θ/σ must be constant, just as in the measurement of visual illumination, v/σ must be constant. Herein lies the main difficulty of the problem, for, in practice, neither homogeneous radiation is used, nor mixed radiation of constant composition, but sources of many different kinds with very different spectra.

θ is supposed to be known, at least approximately; its relation to λ is given by a curve similar to IV in Fig. 41. Only relative values can be given; for θ has not yet been

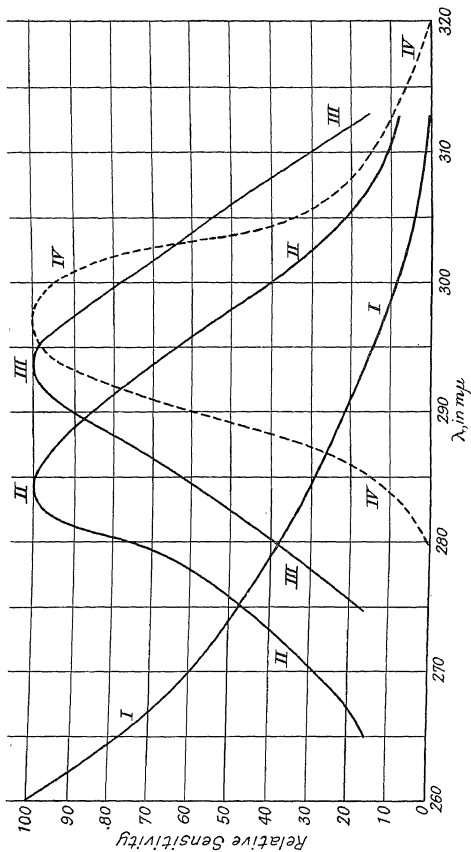


FIG. 41. ERYTHEMA CURVE AND RELATIVE EMISSION OF CADMIUM CELLS WITH CERTAIN FILTERS
 I. Unscreened cadmium cell II. Cadmium cell with filter I III. Cadmium cell with filter II IV. Erythema curve
 (The curves are plotted on different scales to give equal maxima.)

defined in a way which would give absolute values any meaning. It has been determined experimentally by observing the "erythema dose," that is to say, the least exposure to radiation that will cause reddening of the skin. It is assumed that this dose is given by a formula similar to (33), in which $\theta(\lambda)$ is replaced by another magnitude $\theta'(\lambda)$, such that the ratio θ/θ' is independent of λ . For photoelectric dosage we require a cell, or combination of cell and filter, with an effective emission curve similar to the θ curve.

No cell without filter is known to have an emission curve at all similar; for no known cathode (with the possible exception of calcium) has a maximum below $350\text{ m}\mu$; all have curves of form *A* (Fig. 2) in this region. Filters appear, therefore, absolutely necessary if the θ and σ curves are to be at all similar; and since the form of the curve must be imposed by the filter (if it can be found) rather than by the cathode, the best cathode will probably be that which has the maximum emission in this region regardless of its emission elsewhere. This cathode is probably lithium, though the facts are very uncertain (see page 46). So far the appropriate filter does not seem to be made; certain glasses will give the steep rise of the curve on the short wavelength side; the limitation on the long wavelength is likely to present more difficulty.

But perhaps this difficulty might be surmounted by using a cathode having a threshold near the long wave limit of the erythema curve. Cadmium is such a cathode, having a threshold at $313\text{ m}\mu$. Curves I, II, and III in Fig. 41 show the emission of the cadmium cell unscreened and screened with two filters that give fair approximations to the erythema curve. The agreement is not good; it might possibly be better if a metal with a rather longer threshold were adopted, e.g. silver ($339\text{ m}\mu$) or zinc ($343\text{ m}\mu$), for the emission is very small for some distance on the short wavelength side of the threshold.

The problem is, therefore, not yet solved; and, indeed, it does not seem likely of immediate solution. For the medical facts upon which everything turns appear much less certain than has been suggested so far. The actual position is that medical men are using unscreened cadmium cells to determine therapeutic doses from sources as various as

mercury and tungsten arcs. But the response of such cells to the mercury arc arises almost wholly from the line at $254\text{ m}\mu$, which lies outside the whole of the erythema curve, while its response to the tungsten arc arises partly from within it. Moreover, therapeutic action is attributed to sources (such as incandescent tungsten in quartz bulbs) which excite no appreciable effect at all in the cadmium cell. Either current methods are entirely misleading, or the erythema curve does not determine therapeutic effect. The whole subject of "ultra-violet dosage" seems enveloped in a black fog of contradiction; as in the early days of X-rays, medical men are asking for the physical measurement of something that is as yet physically undefined; progress must come from the physiological rather than the physical side.

But if the medical world is determined to use photoelectric methods for dosage and undertakes the responsibility for doing so, the question of the best method of measurement is one on which a physicist may offer advice. However, even here, a full discussion would be out of place, because the methods adopted are sure to be those at present in use for measuring X-ray dosage by ionization methods. The currents concerned are generally of the same order, and the apparatus is likely to be used by the same personnel. The prime requisite is that it should be portable, and need no skilled attention; this is most likely to be attained by the use of either very simple or very elaborate methods. In the first class, attention may be drawn to the ticking electro-scope, developed originally for X-ray dosage; in the second come elaborate valve amplifiers connected to the cell by long leads. The problem of ultra-violet light is simpler than that of X-rays, because no elaborate shielding is necessary to prevent the rays reaching parts of the apparatus other than the cell.

CHAPTER XV

COLOUR

Colour and Spectral Distribution.

COLOUR has no meaning apart from vision, and no instrument but the eye can determine finally and universally whether two lights are of the same colour. But it is closely connected with the spectral distribution of the light, that is to say, with the function $W(\lambda)$ that gives the power of the spectrally resolved radiations of wavelength λ . If two lights, denoted by suffixes 1 and 2, are such that W_1/W_2 is the same for all values of λ (or for all values of λ within the visible spectrum), then the lights are of the same colour. But the converse of this proposition is not universally true, and lights of the same colour may have different spectral distribution.

The only way to determine colour with perfect certainty and generality by photoelectric cells, or any other physical method, is to determine $W(\lambda)$. We must measure the product $\sigma(\lambda)W(\lambda)$ for each wavelength and know $\sigma(\lambda)$.* But when the colour is known to lie within certain limits, an abbreviated method is possible. If the two lights are thrown on two different cells, denoted by suffixes a and b , and the primary photoelectric currents excited in them are I_{a1} , I_{a2} , I_{b1} , I_{b2} , then

$$I_{a1} = A_{a1} \int_0^{\infty} \sigma_a(\lambda) W_1(\lambda) d\lambda \quad . \quad . \quad . \quad (34)$$

and similarly for the other suffixes. A_{a1} depends on the proportion of the total light that falls on the cell a . If the apparatus is arranged so that

$$A_{a1} = A_{a2}; A_{b1} = A_{b2} \quad . \quad . \quad . \quad . \quad (35)$$

* If the colour to be determined is that of an absorbing body and not that of a light, $\sigma(\lambda)$ need not be known; all that is required is the ratio of $W(\lambda)$ for the incident light to that of the light reflected or transmitted. But the problem is then one of absorption, and belongs properly to the next chapter.

and, if it is found that

$$\frac{I_{a1}}{I_{b1}} = \frac{I_{a2}}{I_{b2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

then, unless certain special relations exist between σ_a , σ_b , W_1 , W_2 , either σ_a/σ_b or W_1/W_2 must be independent of λ . If the lights belong to a class for which these special relations are known not to exist, and if the cells have been deliberately chosen so that σ_a/σ_b is not independent of λ , then the only conclusion possible is that W_1/W_2 is independent of λ , and that the lights are of the same colour.

The special relations will not exist in general if the W 's of the class of lights to which 1 and 2 belong form a series of one dimension, and are determined by a single parameter varying monotonically within the class. In particular they will not exist when $W(\lambda)$ is $P(\lambda, T)$ of page 43, and the lights in question are those from complete thermal radiators, so that the colour is completely determined by the temperature T . Then, if the cells have different emission curves, so that σ_a/σ_b varies with the wavelength, if (35) is made true and (36) found to be true, the lights are of the same colour and proceed from radiators at the same colour temperature.

Colour Matching.

This is the basis of a very precise method of comparing temperatures (or at least colour temperatures) of more than $2,000^\circ \text{K}$. The light from one of the two bodies is thrown upon two cells of different emission curves. The cells are balanced against each other as in Fig. 24, and by means of shutters, or similar devices, A_{a1} , A_{b2} are adjusted, so that $I_{a1} = I_{b1}$. Light 2 is then substituted for 1 by a method that ensures that (35) is fulfilled, and that the proportion of the light entering the two cells is unchanged; if $I_{a2} = I_{b2}$, the lights are of the same colour; more generally the relation between the temperatures T_1 and T_2 can be determined from the ratio I_{a2}/I_{b2} .

Of course, the null method, resulting from making $I_{a1} = I_{b1}$, is not absolutely necessary. It was not actually used in the first application of the method, namely, to the colour index of stars. Here it is probably not convenient, and the

differences in colour are so great that great sensitivity is not required. But in application to terrestrial sources, such as incandescent lamps, great sensitivity such as cannot be obtained without this method may be necessary. If it is employed, precision is likely to depend on accuracy rather than sensitivity; for it is not easy to secure that (35) is accurately true, and that the proportion of the light falling on each cell is exactly the same for both lights. Even when the sources are of closely similar form, and the cells are presented to apertures in a diffusing sphere in which they are contained, errors may arise from small differences in the distribution of the light (cf. page 167). One method of removing them is to rotate the cells, so that their apertures travel over exactly the same path; another is to use several pairs of cells, so that the distribution must be symmetrical with respect to the set as a whole, whatever it is with respect to the source.

In order to obtain the different emission curves $\sigma_a(\lambda)$, $\sigma_b(\lambda)$, cathodes of different materials may be used, or the same cathode covered with differently coloured filters, or a combination of different cathodes with different filters. The second alternative is the simplest; but, if large differences between σ_a and σ_b are to be produced (as is clearly desirable), it involves a considerable absorption of light and loss of sensitivity. On the other hand, it might possibly make it easier to secure the accuracy of (35), if the same cell were used with different screens; but then there is a further loss of sensitivity because the best null methods are not possible.

The third is clearly better than the first. For the cells have usually to be placed symmetrically with respect to the light source; in order to secure that $I_{a1} = I_{a2}$, the light incident upon one or the other will have to be cut down; the difference between σ_a and σ_b may be increased by cutting it down with a filter that tends to increase that difference. Sodium and rubidium cells have generally been used. The data on page 51 suggest that potassium would have been better than sodium; and nowadays a thin film cathode would certainly be used in place of rubidium.

In the most precise work, precision was limited by the constancy of the lamps; a change of 1 part in 5,000 of the voltage applied to the lamp could be detected, corresponding

to a change of 0.3° in a temperature of $2,400^\circ \text{K.}$, or a change of about 1 part in 2,500 in the ratio I_{a2}/I_{b2} . A highly-skilled observer can detect by eye a change of about 3° . But precision of this order would be very difficult to obtain in general pyrometric work, because of the need for securing that (35) is true.* We have heard that a photoelectric pyrometer based on this principle is being used, in which the alternating light method of page 168 is used, the cell being covered with differently coloured filters; but we do not know how, or in what measure, the difficulties are surmounted.

Colour by Absorption.

Changes in hue (and we have so far used colour in the sense of hue) are often accompanied by changes in shade, so that the total light emitted varies with the colour; the colour may then be discriminated more conveniently by the change in the quantity than in the quality of the light. When the lights are emitted directly from a source, as in the examples just mentioned, discrimination by quantity is not easy, because the area of the source, the light from which reaches the cell, has to be kept constant. In lamps, for example, though the total light from a given area of the filament varies with the temperature concurrently with the colour of the light, it would not be easy to distinguish changes in total quantity due to changes in the area from those due to changes in temperature.

But when the light is that reflected from or transmitted by some body or medium, the relative advantages of discrimination by quantity and discrimination by quality are reversed; colours arising from absorption are usually best identified by measuring quantity, and therefore fall within the scope of the following chapter. It must be remembered that in this matter estimation by the eye may be very misleading; for the eye is much more sensitive to changes of quality than to changes of quantity. A good example is provided by the problem of titration by certain indicators, of which methyl orange is typical (see page 201). The eye detects the end point best by the change in the hue of the transmitted light, but to the photoelectric cell this change

* Research Staff of the General Electric Co., *Journ. Sci. Inst.*, ii, 177 (1925).

is very small; detection by balancing cells of different emission curves is not at all sensitive. On the other hand, if a filter is interposed which transmits a narrow band of the spectrum in the region of the absorption band of one of the two phases of the indicator, the end point is indicated by a rapid change in the quantity of the transmitted light. To this change the eye is insensitive, and the precision of titration is decreased by the filter when the change is observed visually; but the cell is sensitive to detect changes of quantity, and the precision is greatly increased, when photo-electric methods are used, by interposing the filter and measuring quantity, not quality, of the transmitted light.

CHAPTER XVI

ABSORPTION

The Measurement of Absorption.

By absorption we shall mean here any effect of matter on light that changes the quantity of light passing to a receiver fixed relatively to the source. The absorption coefficient (or, more briefly, the absorption) of an absorber is the ratio in which the light passing to the receiver is changed by its presence; this ratio is usually independent of the quantity of light from the source, but often dependent on its quality.

The absorption coefficient can be determined by two independent measurements of the light received in the presence and the absence of the absorber; but if the source or the cell is liable to variations, there is advantage in making the two measurements dependent in such a way that their ratio is independent of these variations. Methods possessing this advantage are almost always used in precise measurement; we would not suggest that they are not generally preferable, but it should be realized that very constant sources and cells can be obtained, and that these methods are not always necessary. The output in lumens of a suitably-constructed electric incandescent lamp can be maintained constant to 1 part in 400 over many hours; but it must be constructed rather more elaborately than most commercial lamps, and the voltage across it must be controlled to 1 part in 1,500 by means of a potentiometer. The output as measured by a potassium photoelectric cell varies rather more rapidly with the voltage; on the other hand, the total power output, as measured by a thermopile, varies much less rapidly. If the absorption is independent of the quality, there is a valid reason for preferring a thermopile to a photoelectric cell as a measuring instrument; but it is not so weighty as may appear at first sight, because the voltage control necessary for constancy can easily be attained whichever is used; the real limit to constancy is irregularity in the lamp itself, not in the supply.

Three methods have been employed for eliminating variations in the source, or in the cell, or in both—

- I. Rapid comparison.
- II. The Koch resistance (see page 153).
- III. Compensation.

I. In this method measurement is reduced to comparison. A body of known variable absorption is substituted for that of which the absorption is to be measured, and its absorption is adjusted until the photoelectric current does not alter when the substitution is made; the change from one body to another is made so rapidly that no variations of the cell or the source can occur in the interval. If the alternating light method of page 153 is employed, the substitution can be made so rapid that the fluctuations of even the most variable sources, such as open arcs, are immaterial. Otherwise, the source has to be so constant that it will not change materially in the interval between two observations; this condition imposes some limitations, but, nevertheless, the method is very convenient. It is suitable for use with large amplification in the simplest valve circuits; for the irregularity and steady drift that are the main objections to such circuits are of little importance. Another form of it is the method of bracketing in conjunction with automatic registration (see page 171); the unknown absorber and known absorbers with absorptions slightly greater and less than that of the unknown are introduced before the cell in regular succession, and the final result attained by interpolation. This is a method of extreme precision, but requires elaborate apparatus, and a source that will not vary irregularly over periods of a few seconds.

II. The light from the source is divided between a "measuring cell" to which a constant voltage is applied, and before which the absorber is introduced, and a "resistance cell" serving as a resistance in the steady deflection method (see page 112). The method eliminates variations of the source, but not of the cell. The resistance cell is likely to be even more troublesome than the measuring cell; for since the voltage applied to it is low and continually varying, surface charges on the walls may disturb the field; a cell should be used in which the area of bare glass is as small

as possible. Since it does not eliminate variations of the cell, it is not capable of great precision, but it is rapid and convenient. Calibration is needed, because the resistance cell does not obey Ohm's Law. The form of the calibration curve can be controlled to some extent by adjusting the pressure of the gas in the resistance cell. If there is no gas and the voltage curve is concave to the voltage axis as it tends to saturation, the scale will be more open at the larger illuminations. If it is filled with gas at a high pressure the scale will be nearly linear over a wide range. If it is filled with gas to a pressure at which ionization by collision becomes important at low voltage (it can never enter below 16 volts), the characteristic will be concave to the voltage axis and the scale more open for the smaller illuminations.

III. Here two cells illuminated by the same source are balanced against each other as in Fig. 24. In one form of it (*a*) the cells are balanced in the absence of the absorber, and the change due to the introduction of the absorber before one of them compensated by the decrease of the light falling on the other in a known ratio. In the other form (*b*) the cells are balanced with the absorber in place; the absorber is removed and balance restored by decreasing the light on this cell in a known ratio. Both methods assume that the ratio of the effective emission of the two cells remain constant during the period of measurement; but (*b*) is more accurate because it does not assume that the relation between light and current is the same in the two cells. If the restoration of the balance in (*b*) is sufficiently rapid, the method reverts to Class I.

In all these methods devices are required for reducing light in a known ratio, if only for calibration. The devices that have been employed fall into two groups, those depending on a law known accurately, and those depending on an empirical law, which requires further calibration, probably by devices of the first group.

In the first group are—

Optical bench employing the inverse square law.

Rotating sector disc.

Nicol prism.

Partially reflecting plate set at a varying angle of incidence.

Of these the sector disc is probably the best.* As workers in photometry know, the conditions in which the inverse square law are accurately true are by no means easy to attain, and they are harder to attain in photoelectric than in visual photometry. The Nicol prism requires rather elaborate optical arrangements, but is otherwise satisfactory. The partially reflecting plate falls within this group only if its surface is kept very clean; for the textbook law relating the reflection coefficient to the angle of incidence is true only if surface films are avoided. It should be noted also that since the degree of polarization of the reflected (or transmitted) light varies with the angle of incidence, it is not certain that the emission from the cell will be simply proportional to the intensity of the light.

In the second group we have—

Grey wedge.†

Blackened gauze.

Varying current through lamp.

Varying voltage on cell.

The first two are well known optical devices. The absorption of blackened gauze is very nearly independent of the wavelength throughout the entire range of the visible, near infra-red and near ultra-violet spectrum. The grey wedge is not nearly so trustworthy in this respect, especially when made out of a photographic plate progressively darkened. Variation of the current through the lamp, of course, is applicable only when none of the methods that eliminate variations of the source is used; it is useful in very rough work; it must be remembered that the quality as well as the quantity of the light varies. Variation of the voltage of the cell (which changes the effective emission and is equivalent to a change in the amount of light) is useful over a small range.

* The sector disc cannot be used unless Talbot's law is true, i.e. unless the time average of the photoelectric current is determined wholly by the time-average of the incident light. The law is always true if the current is proportional to the light and sometimes when it is not (see G. H. Carruthers and T. H. Harrison, *Phil. Mag.*, vii, 792 (1929)); but it is not true when proportionality fails because a gas-filled cell is being used very near its glow potential (see page 71).

† The "Goldberg" wedge is described in *Zeit. Wiss. Photographie*, xx, 238 (1911).

In Methods II and III, light from the same source has to be thrown on both cells in such a way that the distribution of the light is unaltered by variations in the source. Direct exposure to the source is not suitable when the variations of the source are large; for the distribution of the light usually varies with its intensity. It is better to place the source at the centre of a diffusing sphere (or cube) into which the cells look, screened from the direct light. Or a semi-transparent mirror may be used to divide the light, especially if the light has to be transmitted through an optical system of lenses and mirrors.

Finally, a useful test for the perfection of the apparatus may be noticed; it is the measurement of the absorption of the same absorber for light of different intensity, but of the same quality (unless the absorption is independent of the quality). The same value must always be obtained. The test is convenient also to decide whether the response of a single cell is proportional to the light (see page 76); if it is, measurement of absorption with different lights, calculated from the ratio of the photoelectric currents, will be constant. A series of blackened gauzes are the most suitable absorbers for this purpose.

Examples of Measurement.

The most important application of the true measurement of absorption is to the densities of photographic plates; and in particular to registering microphotometers for determining the densities of star images or of spectral lines. For this last purpose the steady deflection method is generally used with a fibre electrometer. The Koch resistance was introduced first into an instrument of this kind, but it is by no means certain that it leads to greater precision than a fixed high resistance if a suitable source of light is used. The alternative to the photoelectric cell in this application is the thermopile, and it is rather surprising that the latter is being gradually replaced by the former; the thermopile is rather slower and needs larger lights, but it is likely to be more regular. References to some of the instruments that have been described are given in the notes,* but new forms,

* P. P. Koch, *Ann. der. Phys.*, xxxix, 705 (1912); F. Goos, *Zeits. f. Instrumentenkde.*, xli, 313 (1921); E. Bäcklin, *Zeits. f. Instrumentenkde.*,

for which new advantages are claimed, are still being produced; we have no experience on which to assess their relative merits, which, indeed, depend largely on parts other than the arrangement for measuring the light. But one point should be noted; the loss of intensity suffered by a beam of light in passing through a photographic plate is due partly to true absorption, partly to scattering. The proportion between these two parts, and, therefore, the measured absorption, varies with the optical arrangements.

In this application the wavelength of the light is immaterial; for though the absorption of a photographic plate varies considerably with the wavelength, all that matters is the varying absorption of different parts for the same light. When the absorption for homogeneous light has to be measured, and its relation to the wavelength determined, the amount of light available is usually limited; the cell is preferable to the eye or the thermopile in the visible region, because it is more sensitive, especially to the shorter wavelengths. In ultra-violet light it offers the only alternative to the photographic plate, and has usually the advantage of accuracy; the best of the thin film cathodes (see page 34) can be used for measurement in the near infra-red, at least as far as 1000 $m\mu$, and are a serious rival to the thermopile. Photoelectric methods have actually been used for measuring the transmission of light filters, including as an important class glasses which transmit in the region of 300 $m\mu$, and the absorption spectra of various chemical compounds, with a view both to determining their structure and to using their absorption in chemical analysis.* This last use leads naturally to photoelectric titration (see below).

xlvi, 373 (1927); H. Beutler, *Zeits. f. Instrumentenkde.*, xlvii, 61 (1927); G. Hansen, *Zeits. f. Instrumentenkde.*, xlvii, 71 (1927); F. Goos and P. P. Koek, *Zeits. f. Phys.*, xlv, 855 (1927); P. Lambert and D. Chalonge, *Rev. d'Optique*, v, 404 (1926); J. O. Perrino, *Journ. Opt. Soc., Amer.*, viii, 381 (1924); F. C. Toy, *Journ. Sci. Inst.*, iv, 369 (1927).

For relative advantages of thermopile and photoelectric cell, see H. B. Dorgelo, *Phys. Zeits.*, xxvi, 756 (1925), and F. Goos and P. P. Koch, *Phys. Zeits.*, xxvii, 41 (1926).

A general discussion of methods of measuring photographic densities is contained in G. M. B. Dobson's *Photographic Photometry* (Oxford University Press, 1926)

* The most complete studies of the measurement of absorption have been made by K. S. Gibson, *Scientific Papers of the Bureau of Standards*, No. 349, vol. xv, 325 (1919), and *Journ. Opt. Soc. Amer.*, vii, 693 (1923).



Again, photoelectric methods have been used to replace visual observations in polarimetry.* So far, the cell has been used as a substitute for the eye in the judgment of the intensity of light transmitted through crossed nicols. It may be observed that since the photoelectric emission due to light incident obliquely varies with the plane of polarization, the cell might conceivably be used to measure polarization without the usual methods of translating differences of polarization into differences of intensity. But it is unlikely that any method based on this principle would be actually useful.

Lastly, the projected area of an opaque body may be measured by means of its absorption for a parallel beam of light. By this means the variation in the diameter of yarn has been investigated by passing it before a slit through which light passes to a cell.† Other uses of the same principle are probable in the near future.

Grading.

The uses of photoelectric cells in the detection, as distinct from the measurement, of absorption are far more varied. But there are certain applications intermediate between measurement and detection; absorbers have to be graded into a large number of classes characterized by different absorptions, but their absorptions are not truly measured by the assignment of numerals.

The most interesting of these is, undoubtedly, television;‡ here the graded absorption (in our wide sense) of the scene viewed for the light thrown upon it has to be translated into a correspondingly graded brightness of a screen at the receiving end. The principles by which attempts to solve the problem have been made hitherto are well known, but may

and by H. Halban in a long series of papers beginning with *Zeits. f. Phys. Chem.*, xvi, 214 (1920), and leading up to a critical survey in *Proc. Roy. Soc. A* 116, 153 (1927). See also H. L. Tardy, *Rev. d'Optique*, vii, 189 (1928). Mention should be made again of the machine for tracing automatically spectrochemical absorption curves described by A. C. Hardy, *Journ. Opt. Soc. America*, xviii, 96 (1929). See note to Chapter XI, page 153.

* H. von Halban, D. R. patent 386537. (See *Nature*, 119, 85 (1927); J. Kenyon, *Nature*, 117, 304 (1926).

† S. G. Barker and S. R. Stanburg, *British Research Association of the Woollen and Worsted Industries*, publication 105 (1928).

‡ See e.g. *Bell System Technical Journal*, vi, 551-562 (1927).

be stated briefly. In the older method an image of the object is thrown on a disc scanned rapidly by a hole which permits light from different parts of the object to fall in orderly succession on the cell. The corresponding variations in the photoelectric current are amplified, transmitted to the receiver, and there made to cause variations in the potential applied to a neon lamp and, therefore, corresponding variations in the light emitted from it. A hole moving exactly in step with that at the transmitting end allows the observer to see this varying light in positions corresponding to the positions on the object from which came the corresponding light. The relation between position and light intensity presented to the observer is, therefore, similar to that existing in the object viewed. In a later alternative there is no scanning disc between the object and the cell, but the only light thrown on the object is an intense spot which scans it in orderly succession. The cell receives all the light reflected or diffused from the object; the current in it at any instant varies as before with the absorption of the part of the object scanned at that instant.

In either method, the highest possible sensitivity of the cells is desirable in order that the variations of potential communicated to the amplifier should be as large as possible, compared with the inevitable stray disturbances that set a limit to the amplification practically possible. It is impossible to increase these variations beyond a certain limit by increasing the resistance R in Fig. 37, because distortion and loss of amplitude at the high frequencies employed is incurred in accordance with the conclusions of page 149; hence the photoelectric current must be large. Gas-filled cells with large magnifications are always employed. It is then necessary that the distortion mentioned on page 151 should be as small as possible. A linear relation between light and response is desirable; but in the present state of development this is not very important. In the second method, very large cells have to be used—or else a very large number of small cells—in order that as much as possible of the light from the object may be utilized.

Difficulties other than those immediately arising from the photoelectric cells lie beyond our province; but, perhaps, it is relevant to point out why there is so much difficulty. For

the eye, which it is the object of television to replace, is nothing but a collection of photoelectric cells with a very simple optical system; each element of the retina is doubtless a kind of photoelectric cell (see page 20); surely a physical copy of such a system ought to be possible. The reason lies partly in the great number of these elements, and the great number of channels (the individual fibres of the optic nerve) that connect them with the receiver (the brain), but more in the extraordinarily efficient use that the brain makes of the messages it receives. Even if we could use as many cells as there are in the retina, and as many channels of transmission (e.g. separate telephone wires) as there are in the optic nerve, and thus reproduce exactly on a screen the information on which the brain bases its conclusions, it is likely that this information would appear much less complete when it has to pass through the eye once more than when it is communicated directly to the brain, which has had so much practice in interpreting it when received in that particular way.

The problems of picture-telegraphy do not belong here properly because they are those of pure detection.* The cell has usually to distinguish only between two grades of illumination, though in some systems of picture-telegraphy grading is attempted otherwise than by the half-tone system, which reduces differences of shade to differences in the number of absorbent objects. But its photoelectric problems are so similar that it would be pedantic to separate it. The arrangements at the receiving end differ only in detail, and not in principle, from those of the second method of television in which scanning is by a spot of light. Sensitivity is still very important, for though greater illuminations are usually available than in television, very high frequencies are employed and, as we have seen, the accurate transmission of such frequencies requires a large photoelectric current.

"Talking Films," on the other hand, present a problem of grading. The sound is recorded on the film as the undulating boundary of a black area running along the length of

* The best accounts of systems of picture telegraphy are those by F. Schröter, *Zeits. f. tech. Phys.*, vii, 417 (1926); *Elektrotech. Zeits.*, xlvii, 719, (1926). H. E. Ives, *Bell System Tech. Journ.*, iv, 187 (1925); *Journ. Opt. Soc. Amer.*, xv, 96 (1927).

the film. A slit perpendicular to that length, and receiving light from a source, is more or less obscured according as the boundary moves across it. The consequent variations in photoelectric current are translated into sound. Here, in addition to sensitivity, proportionality of current to light over the whole audible range of frequency is important; the demands made on the cell are extremely severe, and much investigation will probably be needed before they are met completely. If they can be met, films may well replace gramophone records and photoelectric cells become, like valves, part of a normal domestic equipment; for the life of films should be longer.

Another problem of grading, though of an entirely different nature, is the automatic sorting of articles according to their colour. It has been attacked in connection with cigars.* The problem is best reduced to one of multiple detection, the articles being subjected to a succession of "go" or "not go" tests. The principles are obvious, but the requisite mechanism extremely complicated.

Detection.

The detection of absorption occurs in its simplest form when a beam of light incident on the cell is cut off by an opaque object or otherwise deflected from it. If the change from light to dark is made to work a relay, the motions of one part of any moving mechanism can be made to control the operations of other parts. The possible applications of photoelectric cells in this manner are innumerable, but in most of them, though they may appear plausible at first sight, further inquiry shows that the proposed function can be better performed in some other way, mechanical or electrical. Nevertheless, there is scope for photoelectric methods, when the moving parts are too delicate to operate a material mechanism, or when they are inaccessible to anything but a beam of light.

One of the most interesting applications of this kind is the control of "slave" clocks by a "master" clock.† A slit in the pendulum of the master permits a beam of light to

* See *Scientific American*, December, 1925.

† M. Schuler, *Zeits. f. Phys.*, xlii, 547, (1927). G. Ferrié and R. Jouast, *Comptes Rendues* 180, 1145 (1925); 184, 56 (1927). J. E. Fox, *Journ. Opt. Soc. Amer.*, xv, 364 (1927).

fall on a cell once in every oscillation; an impulse is thus given to the slave clocks and, through them, to the master; if need be, a signal is emitted. The great advantage of the method is, of course, the absence of any mechanical reaction on the master clock. A further development in the same direction is the attempt to make "clock-stars" record their own passage across a fiducial mark in the meridian telescope, and thus to secure freedom from all personal errors in the determination of the time of their passage. The chief difficulty here lies in making the operation of any relay sufficiently free from time-lag, when the light available is so small; for the photoelectric current has always to charge up an appreciable capacity before it can indicate its presence.

But some very simple applications have also been found useful. Thus, objects too light to operate a mechanical counter can be counted by their interruption of a beam directed on a cell. Again, the level of liquid in a closed vessel (e.g. the water gauge of a boiler) can be detected. Burglar alarms have been proposed in which the presence of any unauthorized object in a room obscures a source of light on one side of it from a cell on the other; invisible light, and especially infra-red light, is usually a part of the scheme; since cells having any appreciable sensitivity to infra-red light have been available, the scheme has become at least technically feasible. The possibility of other forms of secret signalling may interest naval and military authorities. One further suggestion in this group may be mentioned for its ingenuity, though it is not likely to be realized; it has been proposed to replace the tangle of wires in an automatic telephone exchange, connecting the various relays, by beams of light which would not interfere with each other at their crossings.

The use of photoelectric cells in conjunction with the spot of a galvanometer or other reflecting instrument is another favourite suggestion. Here, again, the thermopile is a serious competitor; for by means of Moll's thermo-relay the sensitivity of galvanometers has been brought up to the theoretical limit by a plan essentially the same. But it may be noted that if the current operating the galvanometer is of photoelectric origin, the problem of photoelectric grading, e.g. of coloured objects, is simplified; according as the

deflection falls within one range or another, the spot might set into action a corresponding photoelectric relay.

A much more promising field, which is being developed rapidly, is chemical titration in which the colour change of an indicator or the occurrence of turbidity indicates the end point.* When the colour change is used, the path of the light between source and cell should include an appropriate light filter as well as the absorbing solution; the transmission of this filter should be confined as closely as possible to the region of an absorption band characteristic of the indicator in one of its states, but not in the other; the change in the absorption of the combination of filter and indicator accompanying the change of state is then much greater than if no filter is used.† In these circumstances the photoelectric method is much more sensitive than the visual; moreover, the titration can be made automatic by means of a relay, and the supply of the standard solution stopped when the end point is reached.

When turbidity indicates the end point, it is much better to use scattering rather than absorption (in the narrower sense); a beam of light is passed through the solution, but does not impinge on the cell, which receives only scattered light. The same method provides a very sensitive method of detecting suspended particles—smoke or dust—in air or other gas; in fact, the sensitivity is limited only by the intensity of the beam that is passed through the gas, and the perfection of the optical arrangements in preventing light scattered by anything but the dust from reaching the cell.

It would take far too long to discuss which of the methods of Part II, or of others not described here, is most suitable for each of these applications; but attention should be drawn once more to the methods described on pages 158 and 159, and the priming method of page 162, which are peculiarly appropriate for the operation of relays when detection is to be associated with control.

* R. H. Müller and H. M. Partridge, *Ind. and Eng. Chem.*, xx, 423 (1928). See also *Journ. Sci. Inst.*, vi, 74 (1929).

† It may be useful to record that if methyl orange is the indicator, Wratten filter, No. 35, is appropriate.

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